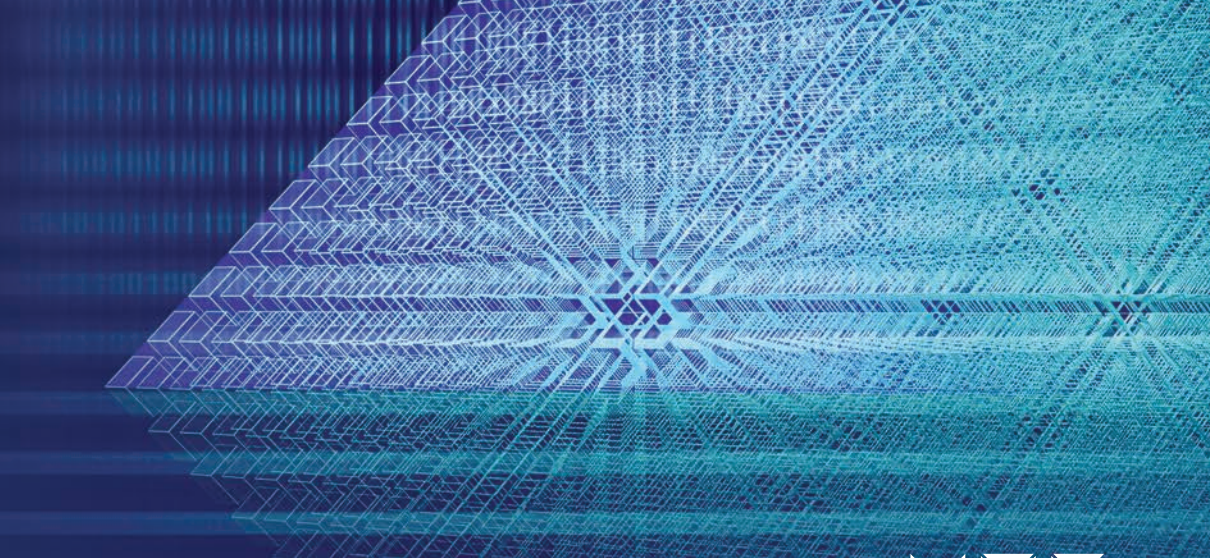

TECHNICAL REPORTS SERIES NO. 486

Guidelines on Soil and Vegetation Sampling for Radiological Monitoring

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GUIDELINES ON SOIL AND VEGETATION SAMPLING FOR RADIOLOGICAL MONITORING

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2019

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FOREWORD

The IAEA places great importance on the dissemination of information that can assist States with the development, implementation, maintenance and continual improvement of environmental radiological monitoring systems, including optimized soil and vegetation sampling programmes. Environmental monitoring of radionuclides in the environment is described in IAEA Safety Standards Series No. RS-G-1.8, Environmental and Source Monitoring for Purposes of Radiation Protection, and in IAEA-TECDOC-1415, Soil Sampling for Environmental Contaminants. The latter was published in 2004 as a guide for analytical laboratories on the sampling of soil for radionuclides. However, the guidelines were only for soil samples.

In 2010, the IAEA published Safety Reports Series No. 64, Programmes and Systems for Source and Environmental Radiation Monitoring, which provides information on practical considerations affecting the design and operation of monitoring programmes and systems in accordance with IAEA safety standards. However, practical application of the Safety Report requires guidelines on sampling programmes for soil and vegetation. Thus, this publication complements the Safety Report and outlines practical considerations for environmental sampling for regulatory bodies and other agencies and organizations involved in the design and operation of source and environmental radiation monitoring programmes and systems, and for experts involved in the assessments of public exposure based on radiological monitoring data.

The IAEA is grateful to all who contributed to the drafting and review of this publication, in particular G. Matisoff (United States of America) and A. Tyler (United Kingdom) for their assistance in its preparation. The IAEA officers responsible for this publication were S. Fesenko, A.R. Iurian and G. Kis-Benedek of the IAEA Environment Laboratories.

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Chapter 1

INTRODUCTION

1.1. BACKGROUND

The impacts of discharges of radionuclides to the environment are assessed by means of environmental monitoring, of which an obligatory component is the sampling of soil and vegetation [1.1–1.5]. The sampling is an important part of radiological monitoring to protect the public and the environment from harmful effects of ionizing radiation, and data from environmental sampling programmes provide information on the amounts of radioactive material discharged and the radionuclide concentrations in the environment. Such data are required to demonstrate compliance with discharge limits and can be used to optimize radiation protection of the population [1.3, 1.4].

The environment can become contaminated from a variety of different sources, which can differ in the pattern of contamination of soil and vegetation, including [1.6]:

(a) Naturally occurring radioactive material (NORM).
(b) Radiation and nuclear accidents and incidents.
(c) Legacy sites:
    — Former military explosion tests sites;
    — Sites of nuclear fuel cycle facilities, including reprocessing of nuclear fuels;
    — Radium contamination.
(d) Sites contaminated by ongoing nuclear activities.

Uncontrolled releases of radionuclides to the atmosphere and aquatic environments can occur from nuclear or radiological accidents [1.7]. Routine activities involving nuclear weapons fabrication and handling, exploitation at nuclear fuel cycle facilities and nuclear power generation have resulted in several severe accidents with substantial contamination and the need for remediation of vast areas, for example Kyshtym (1957), Palomares (1966), Thule (1968), Chernobyl (1986), Goiânia (1987) and Fukushima (2011) [1.7–1.11]. In these cases, data from soil and vegetation sampling programmes were required to assess both the radiation exposure of the public and to determine the actions necessary for public protection, including longer term countermeasures.

Following a nuclear or radiological accident, there is an urgent need to characterize and map the affected areas [1.3]. The selection of sampling points

for soil in agricultural land and forests are coordinated with sampling points for vegetation to provide a comparable and systematic assessment of the total deposition densities [1.6]. The sampling grid takes into account specific land cover features of the contaminated environment and the objectives of the sampling or monitoring programme. Accident scenarios generally result in surface contamination, so the requirements for both the soil and vegetation sampling should be clearly defined in the programme. The choice of sampling sites and approaches can require in situ measurements and geographic information system (GIS) technologies to identify both hot spots (areas with elevated soil and vegetation contamination) or specific environmental compartments that require attention. After sampling in response to an emergency, it is necessary to initiate a monitoring programme to optimize the management of the contaminated area. The sampling requirements of the monitoring programme depend on the characterization of the contamination with respect to current or potential land use. Such sampling programmes are intended to support environmental management and should be optimized by taking into account specific features of the contaminants, the contaminated environment and the potential for the contaminants to spread [1.3]. Defining appropriate remediation and long term protective measures is the major objective of soil and vegetation monitoring programmes [1.6].

Radiation legacy sites provide many examples of contamination scenarios. They are largely a result of inadequate waste disposal practices (e.g. poor disposal practices at early nuclear weapons production sites contaminating soil, water and sediment). Radionuclides are also used for a variety of scientific, medical, agricultural and industrial purposes; and at many sites, the sampling of soil and vegetation is required to monitor compliance with radiation safety requirements. Mining and processing ore can also result in radioactive contamination of the environment. NORM such as ^{238}U, ^{232}Th and their progeny are significant environmental stressors. NORM can also be found in coal and monazite and in many ores containing copper, gold and niobium. The major objective of soil and vegetation compliance monitoring at NORM sites is to identify the risk of exceeding some threshold concentration for the protection of human health and to identify the need for remediation [1.6, 1.8, 1.10, 1.11]. If a significant problem exists, the primary sampling programme should be justified and implemented. The aim is to determine the exact spatial extent of the problem, including depth profiles, and to gather sufficient information to enable a full dose assessment for potential site occupiers and off-site populations [1.10]. If the results of the initial characterization lead to a decision to undertake remediation, then a detailed characterization will be necessary to identify potential remediation options [1.10]. At this stage, data on soil and vegetation are needed to plan the full remediation design.

The nuclear fuel cycle comprises activities such as mining and milling uranium ores, nuclear fuel fabrication, power generation, reprocessing fuel, decommissioning facilities and radioactive waste disposal. During normal operation of a nuclear facility, authorized discharges of radionuclides to the environment can result in an environmental impact, the extent of which depends on the technologies used on the site and the characteristics of the environment [1.3]. Despite the low quantities of radionuclides released at any point within the nuclear fuel cycle, a sampling based monitoring programme might still be necessary. The programme should be designed according to the type and location of the source of radioactivity, the form in which it is discharged and the local environmental characteristics (e.g. wind direction, ground topography, sensitive ecosystems and land uses) [1.3]. Although the sampling programme and selection of sampling points depend on the site and contamination scenario, the sampling design, techniques and equipment can be very similar.

1.2. OBJECTIVE

This publication is primarily intended to provide States with practical advice on the design and implementation of sampling programmes for soil and vegetation within the framework of environmental monitoring. It details the evaluation of ambient concentrations of radionuclides released from both nuclear and non-nuclear facilities, and examines the information required to assess both emergency and existing exposure situations, such as those resulting from nuclear or radiological emergencies or areas affected by past contamination events with long lived radionuclides.

An additional objective is to provide examples of best practice on establishing sampling strategies for different exposure situations based on the experience and lessons from monitoring programmes.

1.3. SCOPE

This publication addresses the sampling of soil and vegetation in terrestrial ecosystems, including agricultural, forest and urban environments, contaminated with radionuclides from events such as radiation accidents, radiological incidents and former nuclear activities. The publication considers sampling strategies and programmes for both emergency and existing exposure situations. It is intended for individuals and authorities dealing with environmental monitoring and includes an overview of current approaches to sampling soil and vegetation for environmental monitoring in different exposure situations. Source and facility

monitoring are not covered by this publication, nor are pretreatment procedures for laboratory analytical methods. The publication also facilitates the use of IAEA safety standards on environmental monitoring (see Refs [1.1, 1.2]) and guidelines from the International Organization for Standardization (ISO) [1.12–1.24] and the International Commission on Radiation Units and Measurements [1.25]. The information in this publication can also be used for training in radioecology and monitoring radionuclides in terrestrial environments. Guidance provided here, describing good practice, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.4. STRUCTURE

General sampling concepts and principles, including the decision process for selecting an optimized sampling programme and the types of sampling, are presented in Chapter 2. Chapter 3 describes sampling strategies for different contamination scenarios. Chapter 4 provides a brief overview of sampling techniques and equipment. The relevant ISO standards for sampling preparation and processing are reviewed in Chapter 5. Chapter 6 focuses on quality assurance and quality control, and Chapter 7 reviews the safety issues outlined in ISO 18400-103:2017, Soil Quality: Sampling, Part 103: Safety [1.14]. Chapter 8 concludes with case studies environmental monitoring following the accidents at the Chernobyl nuclear power plant and the Fukushima Daiichi nuclear power plant, with supporting material presented in the Annex.

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Chapter 2

GENERAL SAMPLING CONCEPTS AND PRINCIPLES

Soil and vegetation can become contaminated when radioactive solids, liquids or vapours are deposited on the surface, mixed with the soil or contaminated from a groundwater source. Radioactive substances in soil can become physically attached to mineral particles and organic matter, and can also become trapped in the pore fluids between soil particles. Freshly deposited aerial contamination lands on the leaf surface. If the leaf matter is not cultivated, it eventually forms part of the leaf litter and is incorporated into the soil and potentially available for subsequent uptake by vegetation. Radioactive contamination often contains a mix of radioactive isotopes, and it is sometimes associated with other contaminants such as petroleum hydrocarbons, solvents, pesticides, herbicides and heavy metals. These factors, together with the properties of the soil can affect the bioavailability of radionuclides in soil.

Although some radioactive substances occur naturally in the environment, contamination of soil and vegetation occurs because of a release of radioactive material into the environment through human activities, including:

— Nuclear weapons;
— Nuclear energy use;
— Accidents and incidents;
— Industrial processes such as manufacturing and mining;
— Nuclear fuel processing;
— Improper disposal of waste;
— Direct application of agricultural chemicals.

Contamination can occur on the site where the release happened or further away if water or wind carries the hazardous materials to an off-site location or region. Mechanisms such as runoff from precipitation, lateral migration of soil water or groundwater, dispersion from a chimney or stack, fugitive dust, soil erosion and mechanical disruption are responsible for the movement of contaminants or contaminated soil. For example, mechanical disruption from industrial activities such as construction, agricultural tillage and site preparation can move contaminated soils or expose previously buried contaminants.

The concern of radioactive contaminants in soil primarily stems from human and ecosystem health risks [2.1]. Health risks depend on the type and

energy of radioactive decay, the duration of the exposure, the contaminant activity and the exposure pathway. Exposure pathways include the following:

— Direct exposure to ionizing radiation;
— Direct dermal contact with contaminated soil or vegetation;
— Inhalation of radioactive vapours and particulate material;
— Ingestion of contaminated water, soils, vegetation and related food products.

Humans can be exposed to ionizing radiation by simply being close to contaminated soil, or they may ingest or inhale contaminants through playing or digging. Vegetation may be contaminated from aerial deposition or uptake through the root system during growth. Radioactivity can then pass from contaminated vegetation to grazing animals and humans that ingest either the plants or the animals. For example, radioiodine fallout is absorbed by grass, which is then consumed by cows, transmitted to milk and then drunk by humans.

In constructing a sampling plan, consideration is given to the potential hazard and risk and therefore the health and safety benefits of undertaking the monitoring, the dynamic nature of the site, and the precision and confidence required in measuring contamination.

2.1. SAMPLING STRATEGY

A sampling strategy is an important component of an environmental monitoring campaign. The fundamental objective of a monitoring programme is promptly to identify a radiological hazard to protect the public and the environment [2.1, 2.2]. A monitoring strategy is defined here as the optimization and deployment of methods, techniques and procedures to meet one or more objectives concerned with the presence of radioactive materials in the environment. Figure 2.1 provides a summary of the components that should be considered when designing and optimizing a sampling strategy and is largely taken from UK guidelines [2.3]. The responsibility of meeting monitoring objectives can lie with nuclear site operators or with those responsible for the protection of the environment and human health.

Clear sampling objectives form an important component of the monitoring principles, which then help to frame the monitoring strategy. The monitoring principles are based on information about the site, such as:

— Site history, including past activities surrounding the site;
— Current site activities;
— Nature of the source;

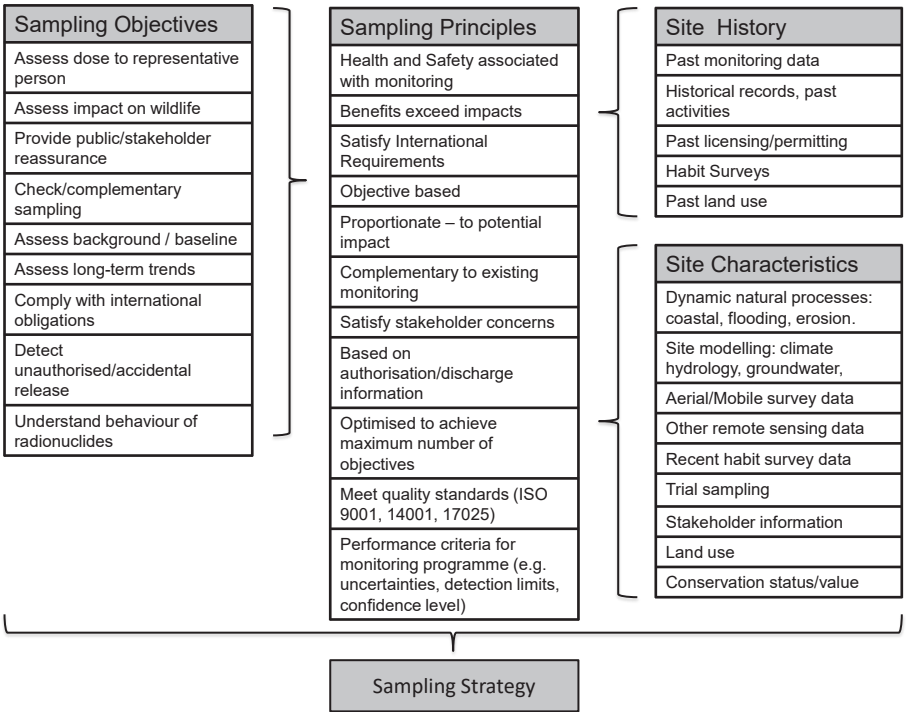


FIG. 2.1. Components of a monitoring strategy.

— Dynamic nature of the site (e.g. coastal erosion, flood events and erosion of material from the site [2.4]);
— Preliminary survey data, including mobile and airborne surveys;
— Modelling of radionuclide dispersion on and off the site;
— Conservation designations;
— Other reliable sources relating to site activities.

This information also guides the health and safety principles of monitoring, where the benefits of the sampling should be set against the risk, and the risk should be minimized to an acceptable level. Similarly, the benefits of the monitoring programme should exceed any environmental detriment and be proportionate to the estimated risk to humans and the environment, taking account of the dynamic nature of the site and the half-life of the target radionuclides. Additional information from airborne, mobile or in situ surveys and trial sampling campaigns coupled with habit data can also contribute to the monitoring strategy. These sources of data drive the size and cost of the monitoring plan. According to UK guidelines [2.3], for example, it would generally not be proportionate if

the dose received from any pathways is less than 0.001 mSv/a, unless meeting objectives associated with baseline characterization. Conversely, where there is high public concern, a site with complex environmental characteristics with the potential for abnormal releases or a dose to a representative person greater than 0.02 mSv/a are factors which may require a programme commensurate with greater impact.

Any monitoring programme should be complementary to existing programmes, avoid duplication and take into account all stakeholder concerns. Existing authorizations and permits provide important information on the source term, but monitoring should also include radionuclides that could be released as fugitive emissions. Information about the type of facility and the stage within the life cycle (e.g. commissioning, operational and decommissioning) should also be considered [2.1].

An optimal sampling programme achieves the maximum number of objectives, undertaken in accordance with appropriate quality standards. It is also fundamental that performance criteria (e.g. monitoring and sampling uncertainty, detection limits and confidence levels) are set to meet the objectives, while simultaneously ensuring proportionality and taking account of the urgency of the information required.

2.1.1. Sampling objectives

Before implementing a sampling programme, its objectives should be established, as they are the main determining factor in establishing the sampling strategy and protocol. The primary purpose of sampling may be to establish background levels or to determine the nature of the contamination for a specific site. The accuracy with which this is established depends on the nature, extent, impact and immediacy of the contamination. Monitoring objectives include the appropriate mechanism for detection of unusual, unforeseen or changing conditions for relevant receptors and exposure scenarios, support for legal or regulatory action and provision of credible data for evaluation of the threat to public health [2.2–2.6]. A monitoring programme should be implemented:

(a) To help safeguard the environment;
(b) To assess hazard, risk and effective response arrangements;
(c) To provide public reassurance;
(d) To assess the impact on wildlife;
(e) To assess the dose to a representative person;
(f) To generate data to serve as a reliable database, to establish a baseline, or to substantiate compliance with laws and regulations;

(g) To provide an independent check on the monitoring or modelling undertaken;
(h) To detect abnormal, fugitive and unauthorized releases;
(i) To support legal or regulatory action or to be used in ascertaining compensation and liability in case of spills or accidents;
(j) To delineate boundaries for clean areas or to establish priorities and thresholds for the cleanup of contaminated sites;
(k) To ascertain the type of treatment or disposal required for cleaning contaminated sites;
(l) To understand or assess the long term trends on the behaviour of radionuclides in the environment or the accumulated impact from licensed discharges.

A post-restoration monitoring programme can be performed to detect and quantify any residual contamination. These data can be used to evaluate the effectiveness of remediation goals and criteria [2.7].

2.1.2. Soil and vegetation sampling plans

Soil and vegetation sampling plans determine the following:

— Position and density of sampling locations;
— Frequency of sampling;
— Sampling procedures;
— Sample preservation;
— Analytical methods;
— Data quality requirements and safety precautions to be observed during sampling;
— Subsequent handling of soil samples.

The monitoring plan needs to consider the prior, current and future use of the site of interest and take account of the change in site use over time. In some cases, the monitoring objectives can be achieved based on the same sampling plan. However, different samples and sampling plans are often required to fulfil a large set of objectives. ISO 18400-101:2017, Soil Quality: Sampling, Part 101: Framework for the Preparation and Application of a Sampling Plan [2.5], lists the following major steps to be considered:

— Collection and evaluation of background information;
— Delineation of areas to be investigated;
— Determination of objectives for the whole investigation;

— Establishment of sampling procedures and a sampling protocol and adherence to quality standards (e.g. Refs [2.8–2.10]);
— Identification of all safety precautions that will be used and dissemination of information to landowners and local authorities;
— Identification of all the parameters to be determined (i.e. radionuclide of concern);
— Documentation of information required to interpret results;
— Consideration of quality assurance and quality control;
— Determination of the soil and vegetation sampling strategy;
— Selection of sampling techniques;
— Documentation of contractual arrangements for sampling and management arrangements;
— Estimation of costs.

Before sampling, the necessary permits and approvals are required, for example from governmental authorities (national, regional and local), the landowner or the land user. For some sites, it may be advisable to inform the public and local inhabitants of the planned sampling, especially if it could lead to local disruption. Sampling as part of an established monitoring programme can be covered by any permits in force. However, this needs to be verified before work commences. Soil sampling in monitored or controlled areas (restricted access areas) can require additional permission. Any existent sampling programme should be reviewed for its suitability for the new monitoring programme. Any prior programme needs to be examined for completeness, plausibility and validity, and any safety and technical aspects (see Chapter 7). In addition, the sample preservation and integrity of storage and transport to the laboratory and disposal of sample material have to be affirmed.

In any case, all preparative measures should be completed before any sampling commences, and the monitoring principles, site history and characteristics also have to be established (see Fig. 2.1). A clearly defined set of objectives can help when designing a monitoring strategy that satisfies the requirements of more than one objective as efficiently as possible. The benefits of sampling have to exceed the adverse impacts that any programme could have on the environment and have to comply with health and safety requirements. The monitoring should take account of stakeholder concerns and complement any existing monitoring being undertaken. Clear performance criteria for the monitoring programme should also be proportionate to the hazard and risk posed by the site to wildlife and public health.

ISO 18400-101:2017 [2.5] finds that the applicability of a sampling technique, the selection of the sampling equipment and the sampling methods also depend on the objectives of the sampling, the strata to be sampled, the

nature of possible contamination and the examination or analyses required to be performed on the samples. It lists the site specific information that should be available and considered when planning any monitoring programme as the following [2.5]:

— Size and topography of the area;
— Nature of the soil and vegetation;
— Indication of lateral and vertical variations of soil and vegetation type;
— Dynamic natural processes acting on the site (e.g. erosion, flooding, tidal inundation and earthquakes);
— Models of site hydrology and climate;
— Geology and pedology of the site and surrounding area;
— Remotely sensed data, aerial and mobile radiometric and geophysical survey data;
— Results from trial monitoring;
— Groundwater depth and flow direction;
— Sample depth, taking into consideration future uses of the site, including depth of excavations, foundations and installations below ground;
— Presence of building and obstructions such as foundations or hardstandings, buried tanks and underground services (e.g. electricity, sewers and cables);
— Previous use or treatment of the site;
— Presence of concrete or tarmac pathways, roadways or hardstandings;
— Safety of the site personnel and protection of the environment;
— Growth of vegetation leading to extensive root development;
— Presence of unexpected water pools or water saturated ground;
— Presence of tipped material above the level of the site, or material from the demolition of buildings;
— Location of water bodies at risk from contamination, including surface and groundwater.

How detailed the research into the site history depends on the hazards and risks posed. For sites that could pose a risk to the public, the site history and a review of all potential contaminant sources and all available data and information should be undertaken. If the review is inconclusive, then a retrospective site review is often best practice. Relevant authorities, bodies or companies can be contacted for additional information, as well as any individuals who might remember the site's history. A site review can include the following:

— Past monitoring data undertaken on, or close to, the site;
— Past surveys of public use of the site or in the vicinity;
— Any photos and documents;

— Historic maps, site plans and geodetic surveys;
— Site maps of installations, buildings, foundations, roads, railway tracks, underground and surface services such as pipelines, pipes, bridges, tunnels, cables, sewers, surface runoff diversion systems, drainage systems, underground cavities or underground workings;
— Past licences and permits;
— Production records, including all types of process, the handling of processed materials, on-site and off-site waste disposal, and details of accidents and hazards.

Site access often depends on when the sampling is conducted and can be affected by adverse weather conditions (e.g. frost, heat, heavy rainfall, snow cover, floods and storms). Best practice is to visit the site for a preliminary survey. When sampling radioactively contaminated sites, a preliminary survey using external gamma dose rate measurements or mobile gamma spectrometry can help to identify areas of interest and risks to workers.

2.1.3. Representativeness

Before analysing environmental data, the samples should be representative of the site under investigation [2.11]. Control of source variability in the data is an important part of the performance criteria (e.g. uncertainties, detection limits and confidence levels). The performance criteria should be proportionate to the hazard of the site and the risk posed to public health, the urgency of the results, the dynamic nature of the site, the resources available and whether the benefits of undertaking the investigation exceed its impact. The two main components of variation are temporal and spatial, and the effects of sample variability can be minimized depending on the location criteria, number of replicates and the frequency of sampling [2.12].

Representative samples reflect the properties of interest in the population [2.6, 2.13]. However, it can be difficult to verify that the sample is truly representative. Therefore, the representativeness of the samples is usually justified based on the sample design [2.14]. There is an immense number of potential samples, so only representative samples are collected for analysis. It is assumed they accurately reflect contaminant concentration, and upon these data conclusions about the whole site are drawn. Since important decisions about a site are based on the sampling data, the data need to characterize accurately the actual site conditions.

Contaminants are not usually distributed homogeneously; nor are they usually homogeneous within a soil sample collected as a representative aliquot. Unfortunately, this variability is often ignored in developing a soil monitoring

programme. Instead, data quality is often based solely on the analytical procedures that generate radionuclide activities [2.15]. The goal of representative sampling is to account for the variability introduced in the field by the sampling procedures and the inhomogeneity of the contaminant. The variables include:

— Site conditions;
— Sampling design and approach;
— Collection and field procedures;
— Site variation in the contaminant concentrations.

The inhomogeneous distribution of contaminants is often the largest contributor to uncertainty in the data and is usually not quantified [2.16, 2.17]. Data quality indicators (i.e. accuracy or precision) which characterize the 'reliability' of the analytical data are also affected by the sample preservation, transport and the laboratory analytical procedures, and do not account for spatial variability of the contaminant. Therefore, it does not matter how good the analytical techniques are if the samples do not accurately represent the site [2.16]. For example, Owens and Walling [2.18] find a factor of up to 2 in the variability of ^{137}Cs inventories from different samples collected at a 'reference' site in which neither soil erosion nor deposition was believed to have occurred following ^{137}Cs fallout. It is not uncommon for the concentrations of target analytes in soil samples collected within a short distance (e.g. 1 m) to have differences of 50–100% [2.15]. Furthermore, some radionuclides are strongly associated with the particulate matter, while others are more soluble; so not only do they migrate with time, but different radionuclides migrate at different rates. As a consequence, this often increases the inhomogeneity with time.

Regardless of the sampling scheme, the objective is to collect a set of samples that truly reflects the site. If limited in number, an individual sample should be typical of the location or dominant species type. Alternatively, if an adequately large number of samples is collected, the International Commission on Radiation Units and Measurements (ICRU) recommends they represent the whole population, which includes the possibility of extreme, non-representative samples [2.14]. With a sufficiently large number of samples, a probability based sample collection scheme can be used in which the samples are expected to yield a distribution of both typical and atypical values that adequately reflect the true distribution of the target population. However, the ICRU adds that it is important to recognize that deviations from a random sampling design may introduce non-random error and thus may negate the validity of the sampling plan [2.14].

2.2. SAMPLING APPROACHES

General procedures for sampling soil and vegetation depend on the purpose of the sampling and are adapted to meet the objectives of the monitoring programme. Reasons for sampling soil include:

— Determining general soil quality;
— Preparing soil maps;
— Evaluating fertilizer application;
— Conducting pollution studies;
— Monitoring hazardous substances;
— Performing risk assessments;
— Supporting legal or regulatory action.

Guidelines vary greatly across countries and in terms of whether they are imposed by law, used throughout the whole country, based on ISO standards [2.5, 2.19, 2.20], or whether they were developed by a scientific organization or by a standardization body. The various guidelines affect data quality, representativeness and uncertainty differently. Sampling strategies also vary with respect to sampling scale, the specifications for contamination risk precautions, the protocol structure and the pre-analysis treatment of the soil samples. For example, most States do not require the top organic matter of a soil horizon be sampled separately [2.21]. These differences can often make it difficult to compare data across countries.

Theocharopoulos et al. [2.21] review soil sampling guidelines and protocols from 14 countries in Europe. They observe that soil sampling guidelines differ greatly in their purpose, sampling plan and protocol, sampling pattern and depth, the inclusion or not of the top organic matter, pre-analysis treatment and whether or not the data are mass or volume (area) related [2.21]. ISO 18589 provides guidance on sampling strategies, identification of sampling areas and units, selection of field equipment, the sampling process, field preparation and transport and pretreatment [2.20, 2.22]; they are applicable beyond measuring radioactivity (see also Refs [2.23–2.26]). The sampling plan is established for a specific case and is directly linked to the purposes of the study. ISO 18589-1:2005, Measurement of Radioactivity in the Environment: Soil, Part 1: General Guidelines and Definitions [2.20], recommends the sampling plan:

(a) Define all actions to be utilized in the field.
(b) Identify the human resource needs.
(c) Consider the capacity of the laboratory testing facilities.
(d) Consider the data quality requisites for the interpretation of the results.

(e) Provide sufficient detail about:
- Sampling areas;
- Sampling units;
- Location of sampling points in the sampling units;
- Types of sample;
- Whether the samples are single or composite;
- Number of increments for composite samples;
- Sampling frequency;
- Required mass or volume of a sample, considering the planned tests and anticipated concentration levels;
- Vertical distribution of samples;
- Requirements for archiving material.

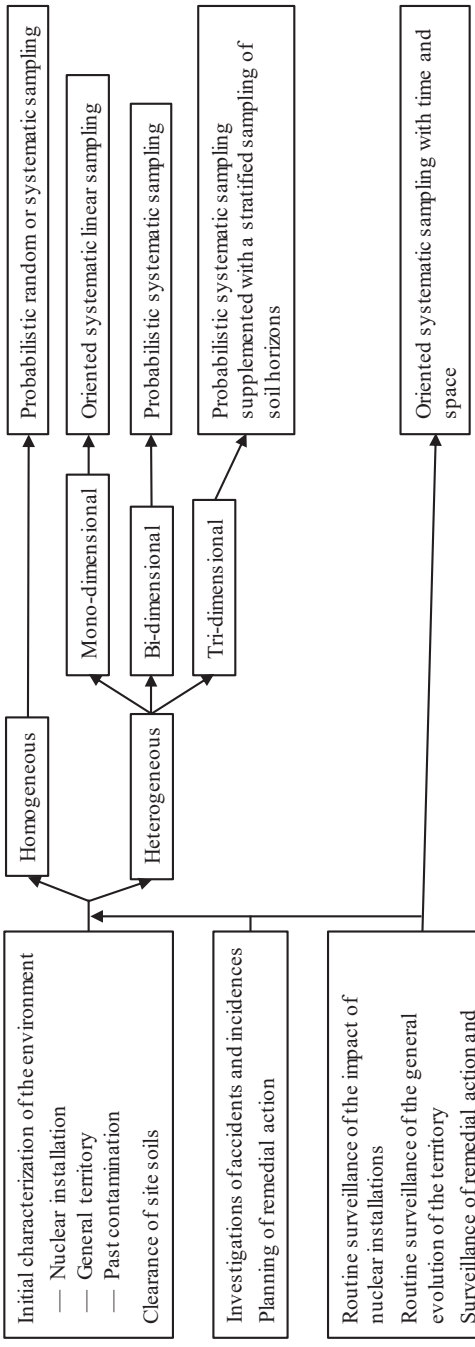
The ISO 18589 guidance also provides example data sheets and flow diagrams for the collection and documentation of sampling (e.g. see ISO 18589-2:2007, Part 2: Guidance for the Selection of the Sampling Strategy, Sampling and Pre-treatment of Samples [2.22], and Fig. 2.2).

2.3. SAMPLING DESIGNS

The sampling design meets the objectives and goals of the study and fulfils the data quality criteria, taking into account social and economic constraints. The design should include: an analysis of historical records of the site, in particular its use, to identify contaminants and sources; an analysis of preferential contaminant migration pathways and areas of accumulation; and a site survey to delineate the sampling areas. The sampling strategy also needs to ensure that the samples are representative of the area under investigation in terms of the deposition and distribution of radionuclides. These early steps in the planning process help to define major design characteristics and can help to set constraints on the number of samples and frequency of sampling required.

The sampling strategy determines the density and the temporal and spatial distribution of the samples and considers the following:

- The potential heterogeneity of the radionuclide distribution at the site;
- Specific site characteristics such as terrain, bodies of water and human structures;
- The required sample mass for analytical measurements;
- Any limitations on the number of samples that can be processed.



Source: Figure A.1 of ISO 18589-2:2007 [2.22].

FIG. 2.2. Selection of the sampling strategy according to project objectives.

An exception is routine monitoring of sites where the radioactive origins and distribution patterns are known. In such cases, it is possible to define a smaller number and location of sampling points than in a purely probabilistic sampling strategy. This subjective selection of the sampling points can be combined with a statistical approach to meet data quality requirements. Alternatively, when the spatial radioactivity distribution is unknown, a probabilistic, or spatially random, strategy is necessary. Probabilistic strategies with random sampling are suitable only if the distribution of the radioactivity is known to be homogeneous. At a site with a heterogeneous contaminant distribution, a systematic sampling strategy can lead to a systematic error in the data. Therefore, it is helpful to have some knowledge of the distribution of these heterogeneities in the different sampling areas. Finally, it is also important to consider the depth distribution of the radionuclides in the soil, for example whether or not the organic surface layer is to be collected as a separate sample and whether soils are to be sampled of uniform thickness or as representative of the different soil horizons [2.22].

The two basic methods are probability sampling and non-probability sampling (also known as judgemental or purposive sampling). In non-probability sampling, the choice of samples is purely subjective, and it is not possible to evaluate the accuracy or bias of the samples. In probability sampling, it is assumed that each sample has a known and non-zero chance of being selected. Samples are randomly selected so that the statistical properties are known and approaches include:

— Simple random sampling;
— Two stage sampling;
— Stratified sampling;
— Systematic grid sampling;
— Systematic random sampling;
— Cluster sampling;
— Double sampling;
— Search sampling;
— Transect sampling.

Sections 2.3.1–2.3.11 describe the different sampling approaches, based on definitions from the ICRU [2.14] and the United States Environmental Protection Agency (EPA) [2.6] (see Table 2.1 for a summary). A representative sampling plan can combine two or more of these sampling strategies depending on the type and distribution of the contaminants.

TABLE 2.1. SUMMARY OF SAMPLING APPROACHES FOR DIFFERENT OBJECTIVES [2.6]

Objective	J	R	2	ST	SG	SR	C	D	S	T
Establish threat	X								X	
Identify sources	X									
Delineate extent of contamination					X	X		X	X	X
Evaluate treatment and disposal option				X						
Confirm cleanup		X	X		X	X	X		X	X
Monitor worst case	X									
Cost effective			X	X				X		
Field screening	X	X		X	X	X	X	X	X	
Use with known trends	X				X		X		X	
Allows for statistical support		X	X	X						
Use with composite samples		X		X	X	X			X	X

Note: Column entries are: J — judgemental sampling; R — simple random sampling; 2 — two stage sampling; ST — stratified sampling; SG — systematic grid sampling; SR — systematic random sampling; C — cluster sampling; D — double sampling; S — search sampling; T — transect sampling.

2.3.1. Judgemental sampling

Judgemental sampling is the only non-probabilistic method discussed here. As defined by the EPA [2.6], sampling locations are chosen according to subjective criteria (e.g. historical information, visual inspection and experienced judgement of the sampling team). With this approach, the sampling team can select a more representative sample to yield more accurate results, or equivalent

results faster or less expensively than other techniques [2.27]. Usually, judgemental sampling is used in preliminary studies to identify contaminants in areas with the highest concentrations, such as near the outflow of a discharge pipe, to evaluate the threat to people and the environment. A sampling spot might be selected on account of visual evidence of pollution (e.g. stressed vegetation, discoloured soil, oily looking patches or the presence of waste), or it may be based on historical site use [2.15]. A small number of samples (<20) are collected. They are not representative samples, so they preclude any reliable statistical interpretation for the whole site. Judgemental sampling is useful for establishing a contaminant threat, identifying sources, monitoring, field screening and when trends are known.

2.3.2. Simple random sampling

Simple random sampling is the arbitrary collection of samples within the defined limits of the area under investigation (see Fig. 2.3). The EPA [2.6] states that random sampling is suitable for areas where an homogeneous distribution of the parameters to be monitored is expected. Sample locations are chosen randomly using a random number table, which ensures independent selection. Randomization is necessary to make probability or confidence statements about the results. Simple random sampling is useful for confirming cleanup, generating statistical support, and for field screening and composite samples.

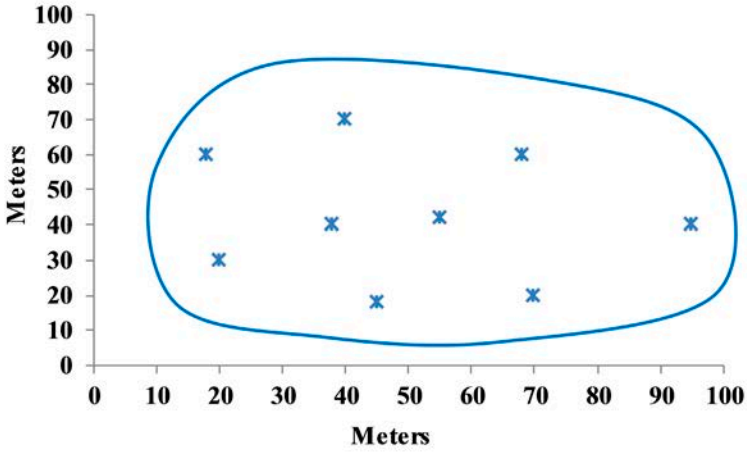


FIG. 2.3. Random sampling.

2.3.3. Two stage sampling

The ICRU [2.14] reports that two stage sampling involves the identification of primary units, of which some are selected randomly, then subdivided, and a fraction of the sub-units are selected randomly. Two stage sampling is useful for confirming cleanup and enabling statistical support, and it can be cost effective.

2.3.4. Stratified sampling

The ICRU [2.14] reports that stratified sampling involves subdividing the population into groups (strata), each of which is expected to be more homogeneous than the entire population (see Fig. 2.4). The individual strata are selected based on prior knowledge or analytical results to have characteristics that distinguish them from other strata and that are known to affect the measured parameter of interest (e.g. sampling depth, soil horizon and contaminant concentration and source). The properties of each stratum are determined by sampling (randomly in the case of a stratified random sampling scheme; systematic in the case of a stratified systematic sampling scheme). Stratified sampling is more complex and requires more prior knowledge than simple random sampling. If the stratum proportions are incorrectly specified, this can lead to biased results in the estimates of the population quantities. Stratified sampling designs have two

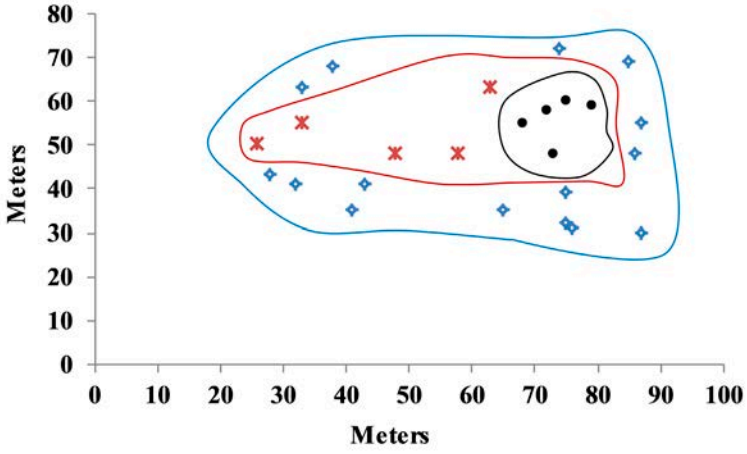


FIG. 2.4. Stratified random sampling based on soil depth.

important advantages over simple random samples: efficiency and improved estimates for meaningful subdivisions of the population. Stratified sampling is useful for evaluating treatment and disposal options, enabling statistical support and for field screening. It can be used with composite samples, and it can be cost effective.

2.3.5. Systematic grid sampling

Systematic grid sampling is the most commonly employed sampling method (see Fig. 2.5). It is generally unbiased as long as the starting point is randomly selected. The area is divided by using a regular square, triangular or herringbone grid, and samples are collected from the nodes (intersections of the grid lines) (see also Refs [2.27, 2.28]). The EPA [2.6] describes that the factors which determine the distance between sampling locations in the grid are the size of the area to be sampled and the number of samples. Systematic grid sampling is often used to delineate the extent of contamination and to define contaminant concentration gradients. The ICRU [2.14] reports that it is often more practical than random sampling because the procedures are relatively easy to implement. However, it can miss important features if the sampling grid resolution is too coarse. Systematic grid sampling is useful in delineating the extent of the contamination, confirming cleanup and for field screening and when trends are known. It can be used with composite samples.

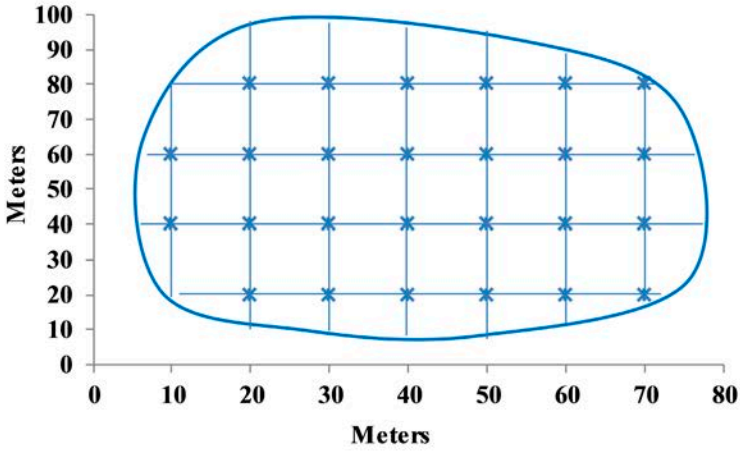


FIG. 2.5. Systematic grid sampling.

2.3.6. Systematic random sampling

The EPA [2.6] finds that systematic random sampling (sometimes called stratified random sampling) is a useful approach in estimating the average pollutant concentration within grid cells. The area is divided using a square or triangular grid (as described in systematic grid sampling), and then samples are collected at random locations from within each cell using the same procedures as simple random sampling (see Fig. 2.6). Systematic random sampling can identify cells that might require additional sampling and analysis. It is useful in delineating the extent of the contamination, confirming cleanup and for field screening. It can be used with composite samples.

2.3.7. Cluster sampling

Cluster sampling can be utilized where members of the population naturally group into clusters or colonies (see Fig. 2.7). Whole clusters of individuals are selected randomly and either all individuals within each cluster are selected and measured or a random selection of a fraction of the individuals are selected for sampling. Cluster sampling is useful when the contaminant patterns are known, for field screening and confirming cleanup.

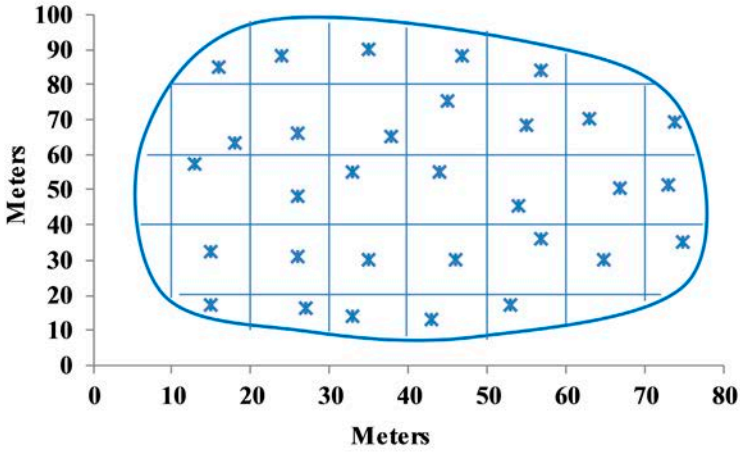


FIG. 2.6. Systematic random sampling.

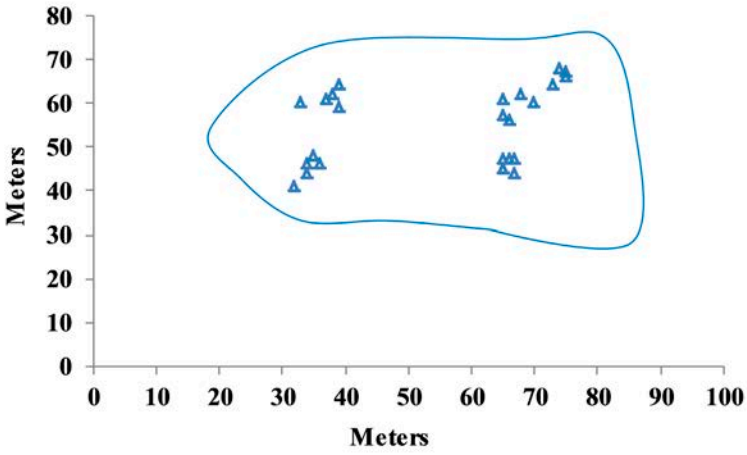


FIG. 2.7. Cluster sampling.

2.3.8. Double sampling

The ICRU [2.14] states that double sampling can be used when two contaminants are strongly correlated, one of which is difficult or expensive to measure and the other is not. This approach requires ground truthing with sufficient numbers of samples analysed by both techniques. Most of the analysis is then performed with the easier or less expensive method. After regression analysis, the data are used to infer the contaminant concentrations of the unmeasured samples. Double sampling can be used with any of the sampling methods, but it is usually best employed in field screening and to delineate the extent of the contamination. It should be noted that the Multiagency Radiation Survey and Site Investigation Manual (MARSSIM) discourages the use of double sampling.[1]

2.3.9. Search sampling

The EPA [2.6] reports that search sampling is used for areas where contaminants exceed applicable standards (hot spots), under assumptions with regard to the size, shape and depth of the hot spots. Either systematic grid sampling or systematic random sampling is used, in which the grid spacing — and hence the number of samples — is determined based on the chance of not detecting a hot spot.

[1] The MARSSIM Manual and resources are available at www.epa.gov/radiation/multi-agency-radiation-survey-and-site-investigation-manual-marssim

If the grid spacing is large relative to the size of the hot spot, there is a greater likelihood of not detecting a hot spot (see Fig. 2.8). However, smaller grid spacing requires more samples. Simple equations have been developed to calculate the number of samples required to hit hot spots of known dimensions and shape. Search sampling is useful for establishing a threat, delineating the extent of the contamination, confirming cleanup and decontamination, and for field screening when trends are known. It can be used with composite samples.

2.3.10. Transect sampling

The EPA [2.6] describes that transect sampling can be used to delineate the areal distribution of contamination and to define contaminant concentration gradients (see Fig. 2.9). Samples are collected at regular intervals at given depths along transect lines. The distance between sampling points is determined by the length of the transect and the number of samples to be collected. The main advantage of transect sampling over systematic grid sampling is the ease of establishing and relocating individual transect lines versus an entire grid. Transect sampling can be used to delineate the extent of the contamination and confirm cleanup. It can also be used with composite samples.

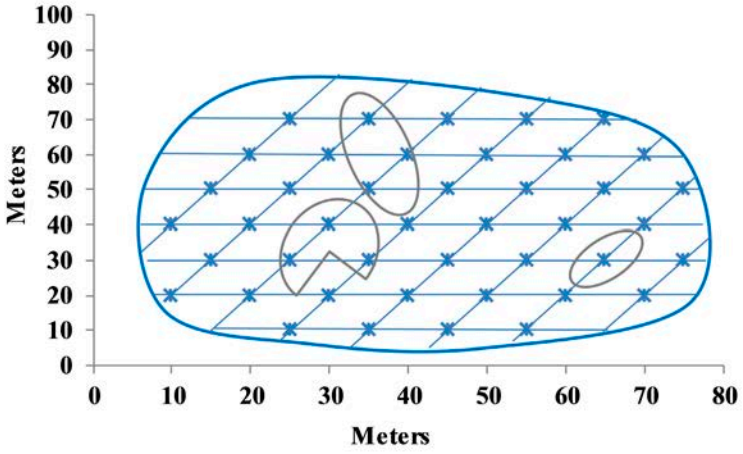


FIG. 2.8. Search sampling using a herringbone grid.

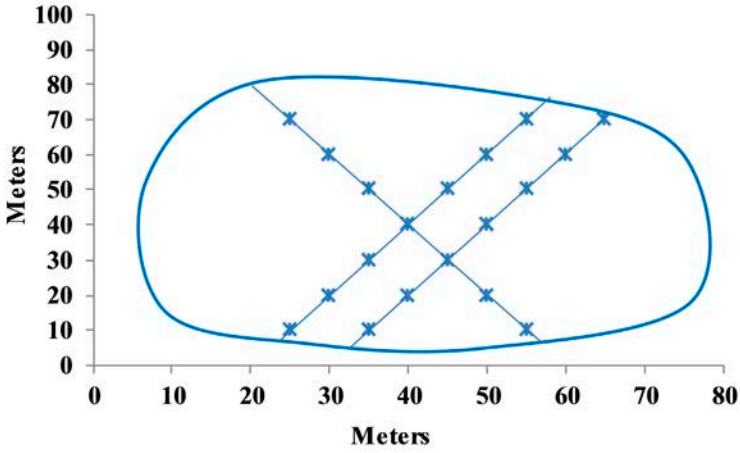


FIG. 2.9. Transect sampling.

2.3.11. Conclusions on sampling design

On the basis of the above discussion, the following conclusions can be reached [2.27]:

— An efficient sampling design should be systematic, stratified and unaligned.
— The herringbone grid has a higher probability of locating hot spots than other patterns using the same number of sampling points, or can achieve the same probability of hitting hot spots with a smaller number of sampling points.
— Judgemental sampling about the likely location of a hot spot can be used to design sampling plans that require fewer samples to achieve the same probability of locating a hot spot. For some sites, this approach could lead to appreciable cost savings, although it does not support statistical interpretations.
— Sampling in two or more stages (e.g. a general aerial survey followed by systematic ground sampling) almost always results in much better estimates of pollutant concentrations at various points for a given total number of samples.
— When two or more substances are analysed on the same site and their values are strongly correlated, it may be possible to achieve adequate spatial characterizations at substantially lower cost by using a technique known as co-kriging. However, this approach has been discouraged.

2.4. OPTIMIZATION OF THE SAMPLING PROGRAMME

A sampling programme is considered a comprehensive approach, from the first step in which the objectives of sampling is defined to the last step of the sampling strategy [2.13]. Optimization of a sampling programme incorporates the main parameters (grid, number, depth and area of sampling) based on prior information, before samples are collected. Optimization should be proportionate to the programme objectives, the risks to the public and the urgency of the results. Although sampling campaigns are tailored and performed in a variety of situations, a generic approach is described in ISO 18589-2:2007 [2.22]:

> "a) Planning process — 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 the area. The sampling strategy shall lead to the knowledge of the nature, activity concentrations, spatial distribution, as well temporal evolution, of the radionuclides, taking into account changes caused by migration, atmospheric conditions and land/soil use.
>
> .....
>
> "b) Planning process — Sampling plan
>
> "The sampling plan shall be developed according to the sampling strategy selected. It shall 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.
>
> "Definitions of the types of sample are given in ISO 18589-1 [2.20]....
>
> "c) Sampling process — Collection of samples
>
> "The collection of any soil samples in the field shall conform to the established sampling plan.
>
> — For sampling of the top layer, a single sample or increments of a defined thickness are taken from each of the selected sampling units.

— For vertical sampling of several soil layers, samples are taken at increasing depth.... Special care should be exercised in order not to mix samples from different soil layers.

.....

"d) Sampling process — 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 soil characteristics."

2.4.1. General framework[2]

The problem of optimization of a sampling programme for environmental monitoring and the representativeness of samples and their measurement became apparent following the accident at the Chernobyl nuclear power plant, when large territories across the European continent were contaminated. Environmental monitoring had tended to sample soil for subsequent measurement in the laboratory. However, aerial surveys, mobile monitoring and in situ gamma spectrometry (see Ref. [2.16]) proved valuable in detecting and delineating changes in soil concentrations (see Ref. [2.30]).

The sampling plan and sample preparation have a fundamental influence on the quality of the results. An increase in the number of samples collected, or an increase in the area sampled, leads to a reduction in error of the contamination level and distribution. However, this comes with increased costs of labour, sampling, sample transport, preparation and analysis. Therefore, the objective of optimization is to obtain an estimate of the distribution of environmental contamination, within a given error, at minimum cost and time. The optimization of the sampling plan thus takes into consideration the personnel resources for sample collection, the time and cost of measurement, and also the quantity and mass of samples, the size of the study area, the depth of sampling, and the vertical and spatial resolution requirements to fulfil the monitoring objectives.

Analytical results are obtained for each sample. Extrapolation of these results to the area or volume from which the sample was collected can only be achieved with some uncertainty. The largest errors during determination of the areal distribution of contamination occur at the stage of sampling planning and the execution of the sampling programme, and not during the measurement of the

[2] This section is based on Ref. [2.29].

sample activity. In practice, the inhomogeneous distribution of contaminants is often the largest contributor to data uncertainty, and it is usually not quantified. Accuracy, precision and other data quality indicators that characterize the robustness of the analytical data are affected by the sample preservation, transport and laboratory analytical procedures, but do not account for spatial variability of the contaminant at the site. It is therefore important that samples are collected in a manner which delivers the confidence level required for effective environmental management [2.15]. For example, after the accident at the Chernobyl nuclear power plant a variety of methods for soil sampling were used. However, the activity estimates from two soil samples collected from points located only several metres apart could differ by one order of magnitude. This led to significant uncertainty in the determination of the areal distribution of contamination, so a governmental commission in Ukraine decided to establish a unified protocol for sampling radioactively contaminated soils.

The soil samples collected and analysed are assumed to be representative of the site. Most of the important decisions about a site are based on these data, so it is essential they accurately characterize site conditions at the time of sampling. This requires that a sample or group of samples collected from the site accurately reflect the concentration of contaminants at the site. Such samples are called "representative samples" [2.5]. This is particularly important in environmental monitoring, upon which the dose calculations are based and policy decisions are made.

Extreme spatial heterogeneity, such as the presence of 'hot' particles (particles of anomalously high activity) in samples can cause large errors in extrapolating the data [2.31, 2.32]. The consequent dissolution of hot particles with different velocities makes the soil contamination extremely inhomogeneous, even on small sites [2.33]. Non-uniformity in microrelief and the redistribution of radionuclides by biogenic factors further influence the non-uniformity of the soil. The radionuclide fallout can migrate deeply into the ground, the intensity of which is determined by the chemical properties of the element, the physical and chemical properties of the fallout, the landscape, and soil and climate characteristics [2.34, 2.35]. The radionuclides are uniformly mixed in the arable (ploughed or tilled) stratum of the soil, and with time they can migrate into the subsoil horizon. Neglecting this vertical migration could lead to significant errors when evaluating the activities and areal distributions of radionuclides [2.36]. It is therefore necessary to know about: (i) the source of radioactive contamination; (ii) the physical and chemical characteristics of the radioactive material; and (iii) its depth migration into soils to obtain a representative sample from a field site.

Plants are primarily contaminated during routine and emergency releases, by direct deposition of aerosol bound and gaseous radionuclides or by direct

contamination (by wind or rain splash) of resuspended radionuclides. Root uptake can also be a significant route, especially for medium to long lived radionuclides. The heterogeneity of radioactive contamination can be lower in plant samples compared with soil, because plant samples are collected from a greater area and the distribution of plant root systems across a larger area effectively averages the heterogeneity of contamination in the soil.

The two types of representativeness are physical and statistical. The physical representativeness of a sample is determined by collecting a single sample within a specified time and space distribution (e.g. by accounting for the vertical migration of radionuclides). The statistical representativeness of a sample is based on the number of samples and the statistical variance of radionuclide contamination in the samples [2.35]. In practice, however, the variance is very seldom known a priori. Therefore, the average value (mean or median) is usually determined from the data, along with an appropriate error and prescribed confidence limit. A very large error may require additional measurements to meet predefined data quality guidelines. To describe the quality of the data, investigators frequently report only the measurement error of a single subsample and extend it to the whole data set, which leads to underestimating the true error and also to incorrect conclusions concerning the contamination characteristics and implications [2.35].

The presence of discrete fuel particles in a soil sample may cause large errors when measuring the activity. For example, the gamma spectrometric measurement of sample activity can vary in the range of one order of magnitude, depending on the fuel particle position in the measuring container (pot or Marinelli beaker) and the container geometry. In addition, the probability of including isolated fuel particles within the subsample depends on the size of the subsample: the smaller the sample, the lower the probability of including a fuel particle in the analysis. In this case, the measured activity of a subsample might not correspond to the activity of the whole sample. Fuel fragments should be isolated and dealt with separately.

The aim of optimization is to minimize the costs of sampling and analysis by defining the minimum number of samples necessary to evaluate the controlled parameters within a specified error, thus ensuring the quality of the monitoring.

Sampling sites with no underlying gradient of contamination are of vital importance when statistically characterizing the contamination of soil and vegetation. These sites are within the limits of which any trend of contamination is absent, and all local deviations of the contamination density have a causal nature (see Fig. 2.2, Section 2.2).

Khomutinin et al. [2.29] describe the distribution of contamination as a continuous function of the locality coordinates $f(x,y)$. Generally, this function has three components:

(a) Trend of contamination: Monotonic component of the density of radioactive fallout conditioned by the global (with respect to the controlled territory) gradient of fallout.
(b) Spot of contamination: Localities with increased or reduced contamination density against a background of the trend.
(c) Random component: Description of the microheterogeneity of radioactive fallout in a point conditioned by technique and process of soil sampling, preparation for measurement, technique and process of measurement.

Each component can be represented by its function of locality coordinates. Combining them yields a contamination density $f(x,y)$ at a specific point. It is possible to present $f(x,y)$ as the sum of functions describing these components (additive model) and as a product (multiplicity model). As $f(x,y)$ is strictly a positive random variable and the log-normal law of probability distribution describes the probability distribution of the values at the specific point, the multiplicity model used can be described as:

$$f(x,y) = f_{tr}(x,y) \cdot f_{st}(x,y) \cdot f_{ac} \tag{2.1}$$

where

$f_{tr}(x,y)$ describes the monotonic trend of the contamination density;
$f_{st}(x,y)$ describes spots of the contamination density against the trend;

and f_{ac} is the random component, independent of the site coordinates. The multiplicity model for $f(x,y)$ can be substituted by an additive model for $z(x,y)$, taking the logarithm where:

$$z(x,y) = \ln\left(f(x,y)\right) \tag{2.2}$$

$$z(x,y) = z_{tr}(x,y) + z_{st}(x,y) + z_{ac} \tag{2.3}$$

The representation of contamination density as Eqs (2.1) and (2.3) is sufficiently general to describe most complex systems. This approach has been successful in mapping the geology and radioactive contamination within the 30 km Exclusion Zone of the Chernobyl nuclear power plant (see Ref. [2.31]).

A key challenge to optimizing the sampling programme is that a regional trend with several anomalies in its background is too difficult to resolve because of site specific characteristics determining the distribution of the radioactive contamination, such as [2.34]:

— Contaminant distribution;
— Presence of localized gradients and hot spots;
— Underlying variability within the landscape;
— Processes leading to the redistribution of radionuclides.

However, an approximate solution can be found when the problem is divided into two consecutive steps:

(i) To define the minimum number of samples required to characterize spatially any trend in the contamination density, within predefined levels of uncertainty, assuming that no anomalies influence the observed spatial trend;
(ii) To define the minimum number of samples required to characterize spatially anomalies within the any trend in the background contamination density, within predefined levels of uncertainty, should this be reasonable.

The appropriateness of the second step is estimated after a statistical treatment of results from the first step, and the demonstration of any contamination density should it occur.

The site is considered to have no gradient within its borders if the density variations due to the radioactive fallout do not exceed the variability caused by random depositional and sampling factors. The identification and separation of sites for sampling can also present a challenge. In the case of gamma emitting radionuclides, mobile or airborne gamma spectrometry systems [2.16] can be used to partition the area under investigation into quasi-non-gradient. Such a method was used widely following the accidents both at the Chernobyl nuclear power plant and the Fukushima nuclear power plant.

Khomutinin et al. [2.29] find that normalizing the contamination density of an arbitrary site on the trend of general form $z'(x,y) = z(x,y) - z_{tr}(x,y) + z_{st}(x,y)$ results in a non-gradient contaminated site ($f'(x,y) = 1$) with respect to the normalized density within the limits of which all divergences of contamination density have a random character.

Thus, Khomutinin et al. [2.29] find that it is fundamentally important to evaluate the statistical performance of the contamination density on uniformly contaminated sites ($f(x,y) = \text{const.}$); that is, sites without a systematic underlying gradient of contamination, or non-gradient sites. The statistical conclusions, obtained for these sites, are the basis of similar conclusions for sites that exhibit an arbitrary trend of radioactive contamination of the form $f_{tr}(x,y) \cdot f_{st}(x,y)$. The fact that any non-uniformly contaminated region can in practice be separated into quasi-non-gradient contamination sites indicates the importance of applying a statistical analysis of the contamination density on uniformly contaminated sites. The underlying assumption in this section is that contaminated sites do not

have any underlying gradient of contamination and are referred to as uniformly contaminated sites.

2.4.2. Depth of soil sampling

Soils can generally be divided into topsoils, surface soils and subsurface soils. Topsoils are directly exposed to the contamination and play an important role in the resuspension and transport of particles. Surface soils and subsurface soils cover the zone where plant root systems are located and represent a reservoir of radionuclides for plant uptake, which is a source of external irradiation.

In situations of radioactive contamination of the soil surface, sampling with depth has to capture the complete profile of the radionuclide under investigation. The deeper the sampling, the greater the sample mass collected and thus the higher are the costs of transport, preparation and analysis.

Different radionuclides have specific physical and chemical properties in the fallout; and in different soil and climate conditions, they have different migration velocities [2.36, 2.37]. The most mobile radionuclides, for example ^{3}H, ^{36}Cl and ^{99}Tc, can migrate with water flow to a depth of 1 m or more in a relatively short period of time, and thus are less likely to be taken up by plants through the root system. Optimizing sampling programmes depends on the aim, and it might require a preliminary study of the vertical distribution of the radionuclides in soil [2.38].

Most of the radiologically significant radionuclides are characterized by high sorption (partitioning) to soil particulates and therefore their migration in most soil types is a relatively slow process. Some radionuclides remain in the upper soil horizons (0–10 cm) decades after deposition. At the Chernobyl nuclear power plant, more than 80% of ^{90}Sr, ^{137}Cs, ^{154,155}Eu, $^{238–240}$Pu and ^{241}Am remained in the surface soil some 30 years following deposition [2.36]. The highest vertical migration rates are exhibited by ^{90}Sr in low humified mineral soil, soddy podzolic sandy soil and sandy loam soil (odzoluvisol) with an organic content of less than 1%. In these soils, 40–50% of the ^{90}Sr activity is in the top 5 cm, and more than 70% of the activity is in the 0–10 cm layer. The highest vertical migration rate of ^{90}Sr occurs under non-equilibrium conditions (in floodplains of rivers and sites after forest fires with light humified sands). In this case, more than 50% of the ^{90}Sr activity can be at a depth of 20 cm [2.36].

Best practice is to sample the soil to the depth of the root system (ca. 10 cm) to predict the contamination in the pasture vegetation of unploughed fields. Sampling at stony sites and sites with heavy sod is difficult, and it is commonly performed to a shallower depth of 1–2 cm. The contamination density within the first one or two years following deposition can usually be determined by sampling the surface (up to ca. 5–10 cm).

Sampling arable fields should be conducted to the base of the topsoil (ca. 20 cm) or to the base of the plough layer (ca. 30 cm) to capture the potential for vegetation contamination. Following a period of about ten years after contamination, best practice is to sample to 20–30 cm because of redistribution of radionuclides in soil through human and animal activity (e.g. mechanical disturbance and soil bioturbation).

2.4.3. Number of replicate samples[3]

Any uniformly contaminated site can be separated into quasi-non-gradient sampling sites. The minimum number of sampling points required to accurately estimate the level of radioactive contamination is determined. Numerous studies on the global fallout of radionuclides from nuclear weapons testing and following the accident at the Chernobyl nuclear power plant (see Refs [2.29, 2.35, 2.39, 2.40]) show that the distribution density of ^{90}Sr, ^{137}Cs and $^{238–240}$Pu contamination on quasi-non-gradient sampling sites in various landscapes (forest, meadow and agricultural land) is satisfactorily described by a log-normal probability distribution:

$$f(C_{so}) = \frac{1}{\sqrt{2\pi} \cdot C_{so} \cdot s_{so}} e^{-\frac{1}{2}\left(\frac{\ln C_{so} - \mu_{so}}{s_{so}}\right)^2} \quad (2.4)$$

where

C_{so} is the soil contamination density of the radionuclide;
μ_{so} is the average log of the radionuclide contamination density of the site;

and s_{so} is standard deviation of the log of the radionuclide contamination density of the site. The parameters of this probability distribution have a well defined physical sense. The contamination density median (also known as the geometric average) is:

$$Me_{C_{so}} = e^{\mu_{so}} \quad (2.5)$$

The parameter s_{so} is the approximate evaluation for the coefficient of variation $W_{C_{so}}$ of the contamination density of the site:

$$s_{so} \cong \frac{S_{C_{so}}}{\overline{C}_{so}} = W_{C_{so}} \quad (2.6)$$

[3] This section is based on Ref. [2.29].

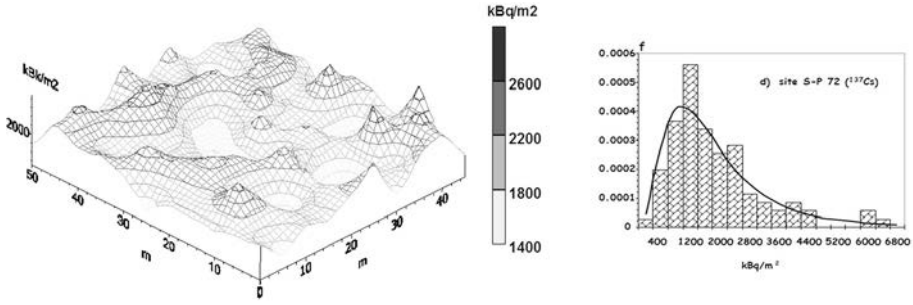
and is independent of the half-life of the target radionuclide of interest.

Radionuclide concentration values are often described by a log-normal distribution [2.14, 2.35]. For log-normally distributed data, the geometric average provides an estimate of the most probable value, and the value itself is less influenced by a few unusually large values than is the simple arithmetic average of the data. Alternative expressions for the central tendency and relative variability of log-normal distributions are the geometric average and the geometric standard deviation, respectively.

Dispersion of the log of soil contamination density in samples, s_{Π}^2, is conditioned by micro-non-uniformity of the site contamination, including discrete fuel particles, by the sample preparation method prior to any measurement. This includes the size selection of the measured subsampling, the error associated with the sampling scheme, and finally by the measurement error.

Typical histograms of ^{137}Cs and ^{90}Sr soil contamination density (in kBq/m^2) and their log-normal approximation of experimental sites for different landscapes and radioactive fallout traces are shown in Fig. 2.10.

Khomutinin et al. [2.29] selected quasi-non-gradient sampling sites in the Exclusion Zone according to two types of radioactive fallout. Control sites were selected where the ^{137}Cs contamination in soil (2–3 kBq/m^2) was generated primarily by nuclear weapons testing fallout. The contaminated areas following the accident at the Chernobyl nuclear power plant provided the second type of fallout, and sampling sites in and outside the 30 km Exclusion Zone. These sites were selected to provide a range of soil contamination, with ^{137}Cs values between 0.05 MBq/m^2 and 30 MBq/m^2. Uncultivated pasture and arable land were selected for both types of fallout, and included flood plains, flat area watersheds and



Source: Figures 2.7 and 2.8 of Ref. [2.29].

FIG. 2.10. Distributions of probability of soil contamination density with ^{137}Cs on quasi-non-gradient sampling sites.

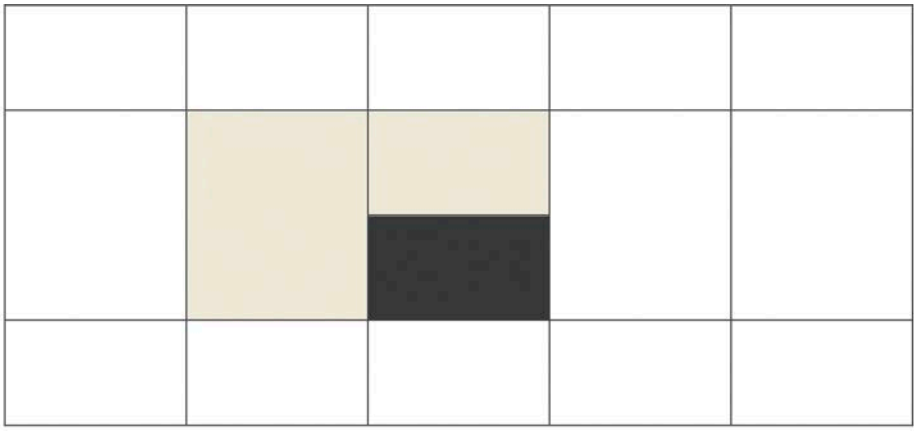


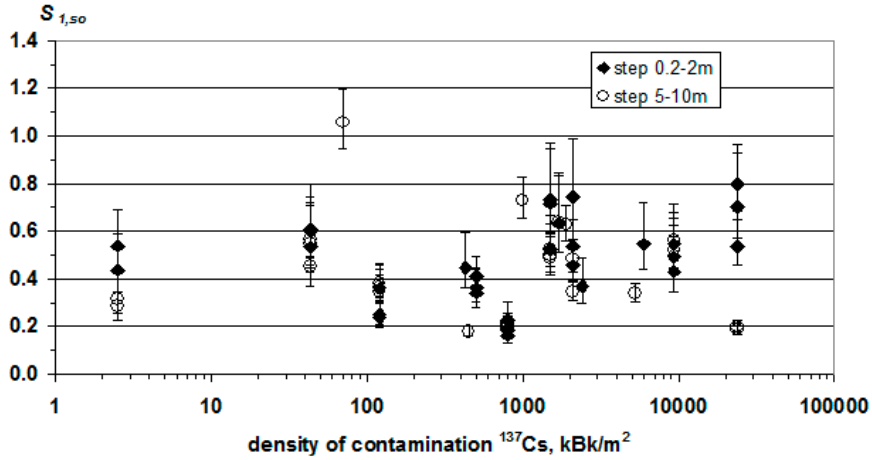
FIG. 2.11. Embedded site scheme for soil and plant sampling.

woods. Sampling was carried out by a regular grid with a 5 m or 10 m pitch, in a sampling area of 0.001–0.013 m^2. The experimental site was usually in the shape of a square, sometimes a rectangle, and the method of embedded sites was used for sampling. The larger main site was subdivided with a large pitch of sampling (10 m). Inside the large grid, a middle site with a 2 m pitch was subdivided into a small site with a 0.1–0.05 m pitch of sampling (see Fig. 2.11).

The key findings from Khomutinin et al. [2.29] are:

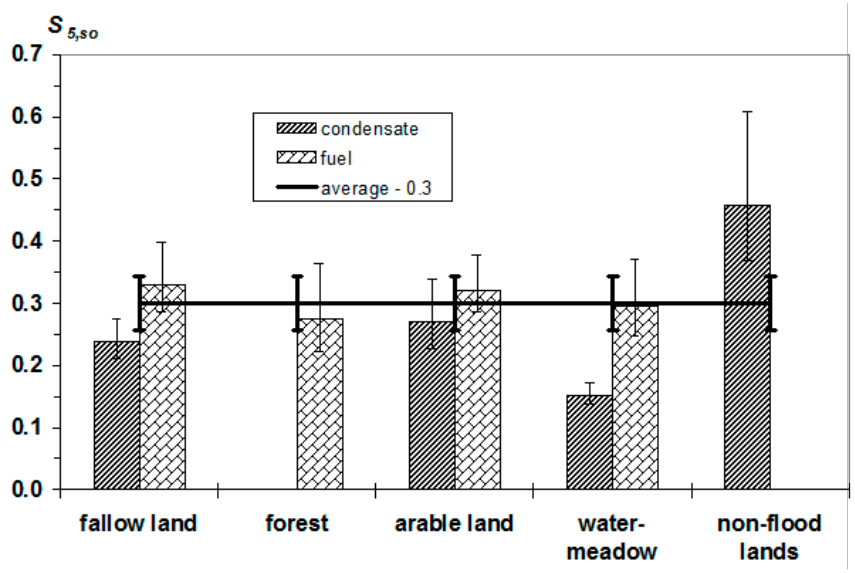
(a) The ^{137}Cs soil density on both uniformly contaminated sites from areas affected by the accident at the Chernobyl nuclear power plant and global fallout sites is satisfactorily described by a log-normal distribution.
(b) The standard deviation (s_{so}) of the log of soil contamination density with ^{137}Cs of uniformly contaminated sites for sampling areas greater than 0.005 m^2 is independent of the contamination density (see Fig. 2.12), type of fallout, landscape (see Fig. 2.13) and its first approximation is $s_{so} = 0.30 \pm 0.09$ for measurements errors of radionuclide content in subsamples of soil samples no greater than 10% at $\pm 2\sigma$.

Soil samples can be single samples or composite (combined) samples. The area of a sample is either single and non-separable (i.e. one core extraction) or a combination of areas adjacent to each other (extraction of adjacent cores). For composite samples, the distance between the individual samples is great enough for the radionuclide content to be mutually independent. The representativeness of a composite sample is higher than for a single sample and the variance is thus lower.



Source: Figure 2.12 of Ref. [2.29].

FIG. 2.12. Influence of density fallout and sampling pitch on the standard deviation of the log of soil contamination density with ^{137}Cs.



Source: Figure 2.15 of Ref. [2.29].

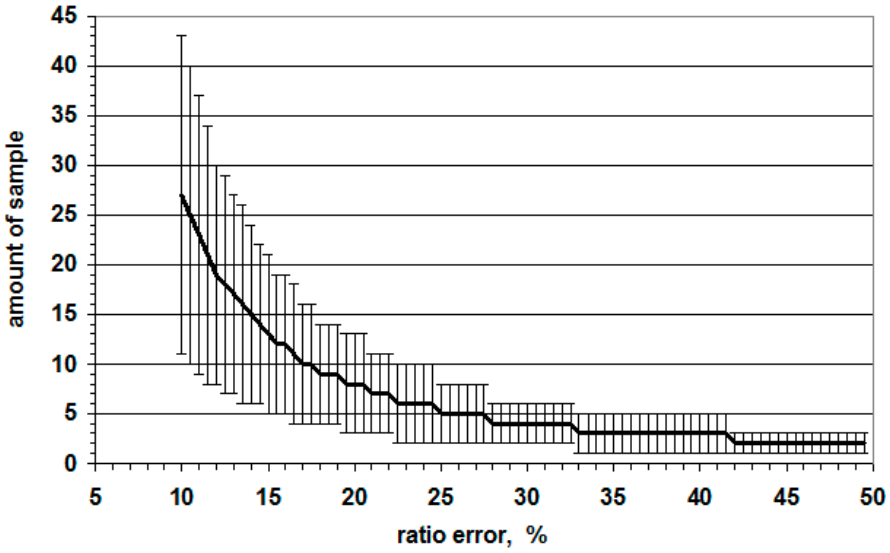
FIG. 2.13. Influence of fallout and land usage on the standard deviation of the log of soil contamination density with ^{137}Cs (sampling area $S_1 = 0.005$ m^2).

2.4.4. Optimizing soil sampling for uniformly contaminated sites[4]

2.4.4.1. Planning the amount of single soil samples

As previously stated, the standard deviation of the log of ^{137}Cs density for a uniform contaminated site, in certain conditions of sample area and measurement error, was approximated as $s_{so} = 0.30 \pm 0.09$. The dependence between the relative error for determination of density of territory contamination with ^{137}Cs and the number of samples collected on the uniformly contaminated site is shown in Fig. 2.14.

Khomutinin et al. [2.29] propose the following example of determining the minimum number of soil samples to within 30% of the median value for ^{137}Cs soil contamination density in a uniformly contaminated site. Under the assumption the sampling and preparation of samples be made according to the above



Source: Figure 6.1 of Ref. [2.29].

FIG. 2.14. Nomogram of the minimum necessary number of soil samples to evaluate the median of soil contamination density with ^{137}Cs in a uniformly contaminated site to a given relative measurement uncertainty value.

[4] This section is based on Ref. [2.29].

conditions and parameters, and that relative measurement uncertainty of ^{137}Cs be around 10% at $\pm 2\sigma$, then no fewer than four independent single samples (on average) or six independent single samples (taking into account the measurement error) are required (see Fig. 2.14). If the relative measurement uncertainty of ^{137}Cs content in soil at $\pm 2\sigma$ confidence exceeds 10%, additional samples (n_{add}) are necessary on account of the additional uncertainty in the average value of ^{137}Cs soil contamination density [2.27]. If the relative measurement uncertainty is 30% at $\pm 2\sigma$ confidence, one independent single sample is required. Khomutinin et al. [2.29] thus conclude that this technique can be used to account for the minimum necessary number of single samples with specified relative measurement uncertainty for evaluating the median soil contamination density at a uniformly contaminated site.

2.4.4.2. Planning the number of composite samples

Khomutinin et al. [2.29] describe that a composite sample is formed by combining several single samples located sufficiently far apart that the radionuclide content in each sample is mutually independent. They consider only the case when all individual soil samples have the same sampling area and volume and also when all the sampled soil is included in the composite sample. The homogenization of the composite sample and selection of suitable subsampling is not executed under field conditions.

As a result of their findings, the official approach in Ukraine to determine radioactive contamination in soil is to use a composite soil sample of five points (based on the envelope sampling approach), where the distance between point soil samples should be at least 1 m [2.33].

The minimum number of soil samples required to estimate the median density of radioactive contamination of soil is defined in Table 2.2. The predicted number of samples depends on the values of δ_γ (relative error of median assessment of soil contamination) and δ_{meas} (relative uncertainty of measurement of radionuclide activity in a sample at 95% confidence level). Table 2.2 shows how the estimate on the contamination density is a function of the number of samples and the measurement uncertainty.

2.4.5. Vegetation[5]

Khomutinin et al. [2.29] also use the same uniformly contaminated experimental sites for vegetation sampling. Plants were sampled from a 1 m × 1 m plot on the same experimental sites as the soil samples. The spatial

[5] This section is based on Ref. [2.29].

TABLE 2.2. MINIMUM NUMBER OF SOIL SAMPLES NECESSARY TO ASSESS THE MEDIAN DENSITY OF RADIOACTIVE DEPOSITION ON THE SAMPLING UNIT [2.41]

Sample type	s_{np} (m^2)	Relative error of measuring ^{137}Cs activity, δ_{meas} (%)			
		10	20	30	40
Single	0.001	64	66	70	75
	0.002	54	56	60	65
	0.003	50	52	56	61
	0.004	48	51	54	59
	0.005	47	50	53	58
Composite	0.003	21	23	27	32
	0.004	16	19	22	28
	0.005	14	16	20	25
		Relative error of median assessment of soil contamination $\delta_{\gamma=0.95}$ = 20%			
Single	0.001	18	18	19	21
	0.002	15	16	17	18
	0.003	14	15	16	17
	0.004	14	14	15	17
	0.005	13	14	15	16
Composite	0.003	6	7	8	9
	0.004	5	5	6	8
	0.005	4	5	6	7
		Relative error of median assessment of soil contamination $\delta_{\gamma=0.95}$ = 30%			
Single	0.001	9	9	10	10
	0.002	8	8	8	9
	0.003	7	7	8	9
	0.004	7	7	8	8
	0.005	7	7	7	8
Composite	0.003	3	4	4	5
	0.004	3	3	3	4
	0.005	2	3	3	4

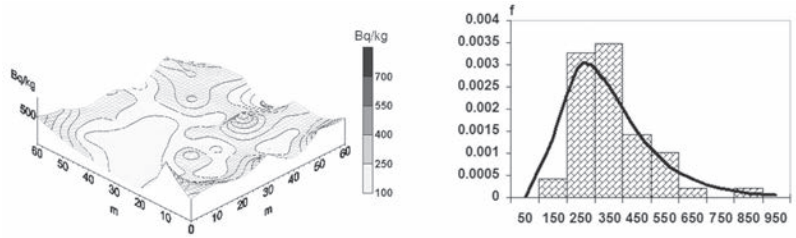
TABLE 2.2. MINIMUM NUMBER OF SOIL SAMPLES NECESSARY TO ASSESS THE MEDIAN DENSITY OF RADIOACTIVE DEPOSITION ON THE SAMPLING UNIT [2.41] (cont.)

Sample type	s_{np} (m^2)	Relative error of measuring ^{137}Cs activity, δ_{meas} (%)			
		10	20	30	40
		Relative error of median assessment of soil contamination $\delta_{\gamma=0.95}$ = 40%			
Single	0.001	6	6	6	6
	0.002	5	5	5	6
	0.003	4	5	5	5
	0.004	4	5	5	5
	0.005	4	4	5	5
Composite	0.003	2	2	3	3
	0.004	2	2	2	3
	0.005	2	2	2	2

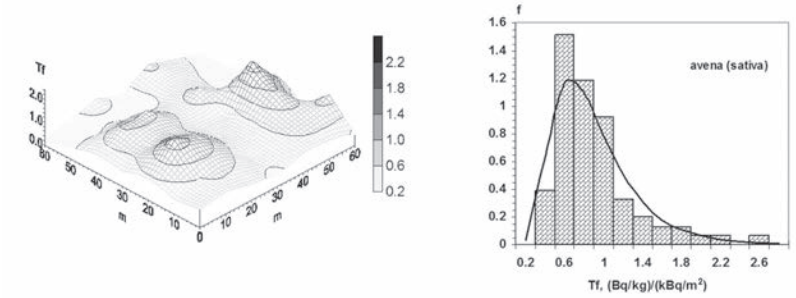
distribution of vegetation contamination and the transfer factor T_f of ^{137}Cs into plants is shown in Fig. 2.15. A log-normal distribution is the simplest theoretical probability distribution that describes the ^{137}Cs content in plant samples selected on uniformly contaminated sites. Khomutinin et al. [2.29] conclude that:

(a) The ^{137}Cs content in plants and the transfer factor of ^{137}Cs into plants on uniformly contaminated sites near the Chernobyl nuclear power plant and on global fallout sites is satisfactorily described with a log probability distribution function.
(b) The standard deviation of the log of the ^{137}Cs content in plant samples does not depend on the contamination density, type of fallout (see Fig. 2.16), or type of vegetation (see Figs 2.17 and 2.18).
(c) As a first approximation of the standard deviation, $s_{so} = 0.37 \pm 0.11$ on the Chernobyl nuclear power plant and on global fallout contaminated land, in areas of less than 1 m^2 sampled for plants, assuming a 1σ measurement error ratio for ^{137}Cs in vegetation samples of less than 10%.

The average standard deviation of the log of the transfer factor of ^{137}Cs in plants does not depend on the contamination density, the type of fallout,



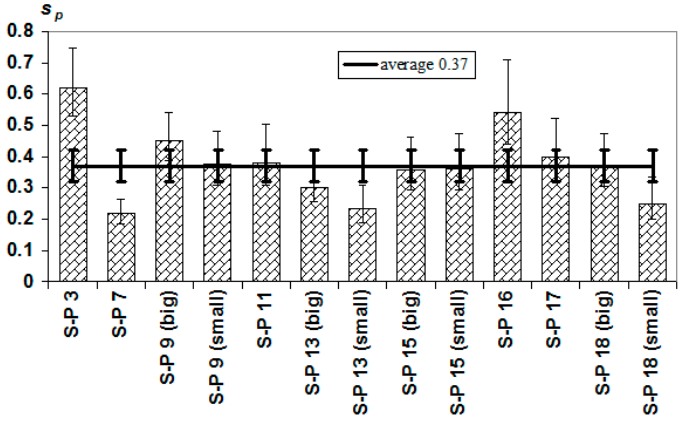
(a) Secale (cereal) contamination with ^{137}Cs.



(b) Transfer factor of ^{137}Cs in the soil–Avena (Sativa).

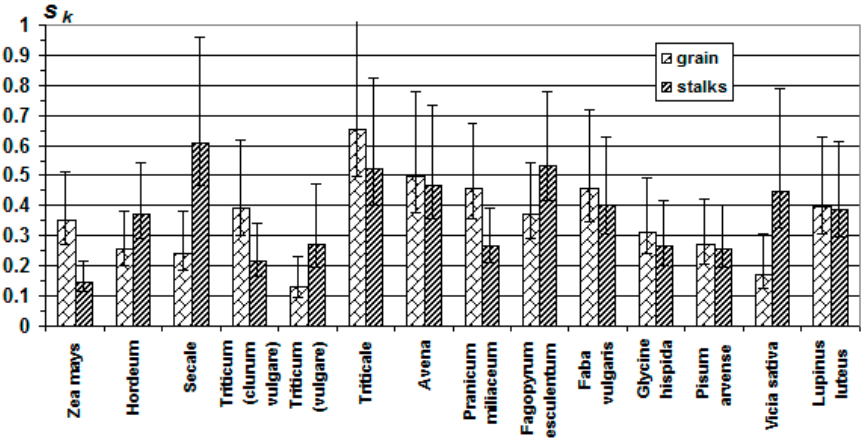
Source: Figures 2.16 and 3.1 of Ref [2.29].

FIG. 2.15. The spatial distribution on the experimental site.



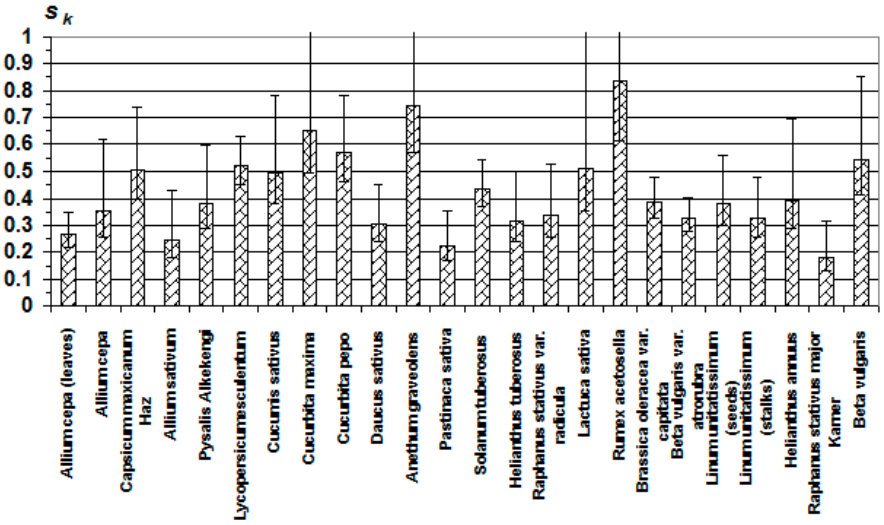
Source: Figure 2.21 of Ref. [2.29].

FIG. 2.16. Values of the standard deviation of the log of the ^{137}Cs concentration in plant samples collected from various experimental sites in the Chernobyl nuclear power plant area.



Source: Figure 3.6 of Ref. [2.29].

FIG. 2.17. Values of the standard deviation of the log of the transfer factor of ^{137}Cs into various agricultural grain crops sampled in the Chernobyl nuclear power plant area.

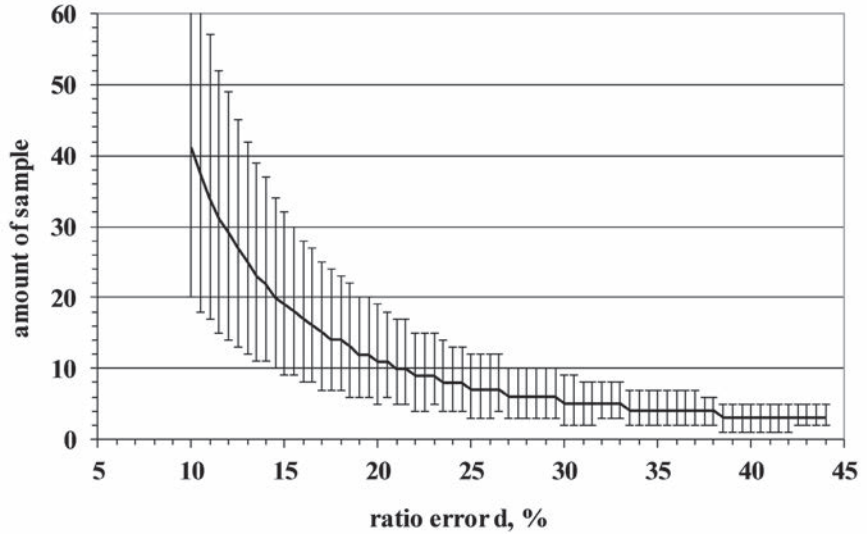


Source: Figure 3.7 of Ref. [2.29].

FIG. 2.18. Values of the standard deviation of the log of the transfer factor of ^{137}Cs into various vegetable and industrial crops.

or the type or part of vegetation sampled. For sampling areas 0.005–1 m^2, $s_{so} = 0.49 \pm 0.06$ can be assumed as a first approximation in conjugate soil–plant pairs, assuming a value of less than 10% relative measurement uncertainty for ^{137}Cs in vegetation samples at 1σ confidence. Figure 2.19 presents the minimum number of samples required to obtain the median ^{137}Cs content in plants at a non-gradient site with a specific relative measurement uncertainty value δ and confidence probability of $p = 0.95$ ($\delta_{inst} \leq 10\%$ at $\pm 1\sigma$ level).

Khomutinin et al. [2.29] propose the following example of determining the minimum number of plant samples to within 25% of the median value for ^{137}Cs content in plants on a non-gradient site. They assume that sampling and preparation of samples are made according to the above conditions and parameters, and that the relative measurement uncertainty for ^{137}Cs activity in soil samples is 10% at $\pm 1\sigma$ level. They conclude that it is necessary to select no fewer than 7 independent single samples (on average) or 12 independent single samples when taking into account the relative measurement uncertainty (see Fig. 2.19).



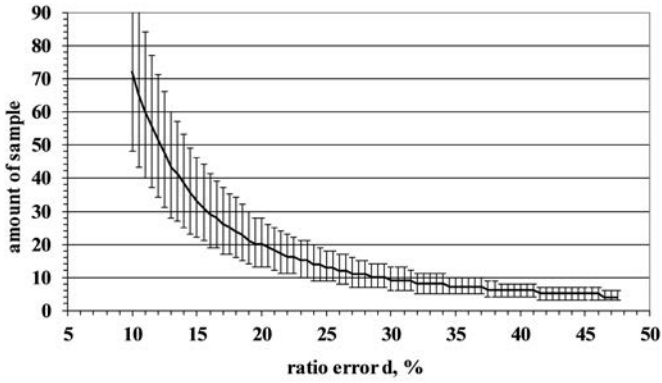
Source: Figure 6.2 of Ref. [2.29].

FIG. 2.19. Nomogram to determine the minimum necessary number of plant samples required to obtain the median ^{137}Cs content in plants on a non-gradient site (sampling area = 1 m^2).

Khomutinin et al. [2.29] state that the problem of obtaining reliable estimates of transfer factors in the soil–plant chain is one of the most significant challenges for both agricultural crops and wild plants when predicting the impact of radionuclide contamination. The accuracy of the transfer factor depends on a large number of conjugate soil–plant samples, the optimization of which is driven by limited resources, high labour costs and expensive analytical measurements. Two frequently encountered problems in radioecological studies are determining the minimum number of conjugate soil–plant samples required [2.29]:

— To calculate the median transfer factor with a specified relative measurement uncertainty value;
— To identify real differences in the transfer factor under different environmental conditions.

The dispersion of the log of the transfer factor of ^{137}Cs from soil to plants does not depend on the fallout density nor on the vegetation type or its different parts. When sampling areas are greater than 0.005 m^2 for soil and less than 1 m^2 for plants, then as a first approximation $s_k \cong 0.49 \pm 0.06$ for conjugate soil–plant samples, assuming measurement error ratio for ^{137}Cs in soil relative to vegetation samples less than 10%, at 2σ confidence. Figure 2.20 presents the minimum number of conjugate soil–plant samples n required to estimate the median of the radionuclide transfer factor with a specific ratio error δ and a confidence probability of $p = 0.95$.



Source: Figure 6.3 of Ref. [2.29].

FIG. 2.20. Nomogram to determine the minimum necessary number of conjugate soil–plant samples required to obtain the median transfer factor with a prescribed ratio error at a confidence probability of p = 0.95.

Possible errors in the estimated number of conjugate samples n ($\pm\sigma$) are shown by the scatter of the standard deviation of the log of the transfer factor and are connected with causal factors that cannot be easily controlled. For example, ten conjugate soil and plants samples are required to estimate the transfer factor with a relative error of less than 25%.

The permissible error δ_γ of the median specific activity in the crop plants at the site (field, meadow or pasture) is determined by the aim and objectives of the monitoring programme and/or as specified by the client. When the value of δ_γ of the median specific activity of radionuclides in plants is undefined, it is generally good practice to keep δ_γ to within 30% of the confidence probability of $\gamma = 0.95$ ($\delta_{0.95} \leq 0.3$).

Depending on the values of δ_γ and δ_{meas}, optimizing the minimum number of samples required to assess the median specific activity of radionuclides in a crop is determined from Table 2.3 or Fig. 2.20. Khomutinin et al. [2.29] use the example of five independent plant samples (≤ 1 m$^{2)}$ which are required with a relative measurement error $\delta_{meas} = 10\%$ to estimate the ^{137}Cs content in vegetation with an accuracy $\delta_{\gamma=0.95}$ of 30%. Alternatively, if $\delta_{meas} = 50\%$, a significant reduction in measurement time can be gained and only seven independent samples are required to achieve the same level of overall accuracy $\delta_{\gamma=0.95}$ of 30% (see Table 2.3).

TABLE 2.3. MINIMUM REQUIRED NUMBER OF POINT PLANT SAMPLES FOR ASSESSMENT OF MEDIAN SPECIFIC ACTIVITY OF RADIONUCLIDES IN THE CROP ON SAMPLING UNIT [2.41]

Relative error of estimate of median specific activity $\delta_{\gamma=0.95}$ (%)	Relative error of measuring ^{137}Cs activity, δ_{meas} (%)				
	10	20	30	40	50
10	39	41	45	50	56
20	11	11	12	14	15
30	5	5	6	7	7
40	3	3	4	4	5

2.4.6. Location of sampling points

Soil and vegetation samples should be collected on open ground which is unlikely to have experienced any disturbance to the deposition pattern. Sampling of depth profiles can capture full soil characterization. However, routine analysis of the depth profile might not be necessary to detect long term accumulation, where the overall inventory is seen to increase. Samples of agricultural soil can be used to study the ingestion pathway, in which it would also be appropriate to take conjugate samples of crops or vegetables at the same location.

Typical, local species are preferable. Care should be taken not to include adhering soil particles in the sample where such particles would most likely be removed during food preparation procedures. Pasture is important because of the rapid uptake of important radionuclides such as radioisotopes of iodine and caesium by animals, particularly cattle, and the subsequent transfer to milk. Pasture should be sampled where wet or dry deposition is expected to be greatest. Samples of milk and undisturbed soil should also be collected at the same locations [2.30].

The sample area should be horizontal and flat, in an open area and away from large trees or buildings. Plants should be uniform in height. Nevertheless, there are situations when it is not possible to choose an open area (i.e. in a forest or urban environment). The ^{137}Cs deposition activity in soil increases by up to two times the further away from the border of a tree crown projection. This might result from the removal processes of radioactive substances from a crown down to the soil surface: the heavier and the thicker a tree crown, the lower the expected radionuclide deposition levels are nearer to the trunk [2.42, 2.43]. In such cases, soil and plant sampling should be conducted at equal distances from those high objects.

2.4.7. Sample area, mass or volume

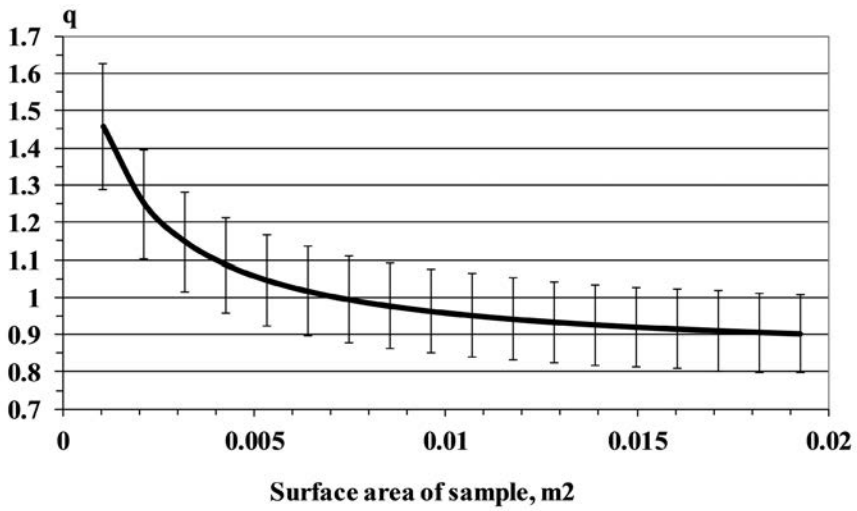
An increase in sample area, mass or volume lowers the measurement uncertainty of the contaminant concentrations in soil or plants, and potentially provides more sample material to decrease the measurement time. However, transport costs and preparation time increase. Selecting these parameters is part of the optimization of the sampling programme. It is assumed that the activity concentration of the target radionuclides is greater than the minimum detectable activity for the detection method being used.

Khomutinin et al. [2.29] show that there is no difference in the standard deviation of the log of ^{137}Cs contamination density in soils for sampling areas not less than 0.005 m^2. The fact that the considered ratio decreases to less than 1 with an increase in sampling area is evidence of the approximation of the dependence

on the sampling area (see Fig. 2.21). They thus find it convenient to accept 0.005 m^2 as a baseline sample area obtained from either an integrated sample of five independent single samples each with a diameter of 3.7 cm (sample area of 0.004 3 m^2) or with another sampling device with a diameter of 4.0 cm (sample area of 0.005 m^2).

For vegetation, areas of 1 m^2 or more are used to collect around 1 kg of sample. Grass is collected down to a few centimetres above the ground and only the green leafy portion of the plants is collected.

The detection limits for environmental sample analysis depend on the objectives of the sampling campaign and the requirements of the monitoring programme. However, there may be typically of the order around $n \times 10^0$ Bq for gamma and beta emitting radionuclides (e.g. ^{54}Mn, ^{60}Co, ^{65}Zn, ^{90}Sr, ^{95}Zr–^{95}Nb, ^{134,137}Cs and ^{144}Ce) and $n \times 10^{-3}$ Bq for alpha emitting radionuclides (^{238}U, $^{238,239–240}$Pu and ^{241}Am) after chemical extraction [2.30]. To achieve these levels of detection, the amount of soil and plant samples are usually 0.1–1 kg for gamma and beta emitting radionuclides, and only a few grams for alpha emitting radionuclides. For example, the density of global fallout deposition of ^{137}Cs in the northern hemisphere is about 2–3 kBq/m^2; therefore, a soil sample in a 0.001 m^2 area might have an activity of 2–3 Bq, which is higher than the minimum detectable activity. With a 20 cm depth of sampling, the volume will be about 200 cm^3 and its activity concentration about 10 Bq/kg.



Source: Figure 2.14 of Ref. [2.29].

FIG. 2.21. Relationship between the standard deviation of the log of the ^{137}Cs contamination density in soils with the area sampled.

2.4.8. Distance between sampling points[6]

When undertaking field sampling for environmental monitoring, selected point samples should be statistically independent and representative of uniformly contaminated sites. This can be achieved by taking samples at sufficiently large distances to avoid correlation, and it can typically be assessed from semivariogram or variogram analysis. Statistical independence is achieved at distances beyond which the maximum semivariance or variance is reached (i.e. the point at which the variogram becomes constant) [2.44]:

(a) Soil samples for ^{137}Cs content, including composite samples of several closely related samples (0.001–0.01 m^2), are considered to be statistically independent when collected at a centre to centre distance of more than 1 m on a uniformly contaminated site.
(b) For vegetation sampling, the centre to centre distance (when the area sampled is ca. 1 m^2) should not be less than 8–10 m in all cases to achieve statistical independence.

2.5. OPTIMIZATION BASED ON SUPPLEMENTARY INFORMATION AND TOOLS

In situ and mobile gamma spectrometry surveys provide valuable additional information, but sampling plans optimized using a geographic information system (GIS) coupled with statistical modelling approaches that utilize ancillary data can be highly valuable and tailored according to the sampling objectives. Such ancillary data includes altitude, climate, soil, vegetation, land use, population density, and wildlife and conservation designations.

2.5.1. In situ measurements

In situ measurements provide a spatially integrated estimate of the radiation field. Field radiation measurements can include dose rate measurements using hand held radiometers, gross measurements of beta or gamma activity, and energy specific measurements of gamma radiation [2.45]. Although simple instruments may be valuable in locating or delineating areas of high activity, they have to be used with care at levels near to the natural background if statistical counting effects or local variations in background are not to be misinterpreted as variation in the contaminant. Gamma spectrometry based techniques can resolve

[6] This section is based on Ref. [2.29].

radionuclide distributions, but absolute interpretation may be influenced by variations in the vertical distribution of radioactivity in the soil [2.44].

The gamma dose rate or beta particles flux density can be used to determine sample locations to be surveyed. The distance between the survey grid or transect lines depends on the distance from the source of contamination and the likely direction of contamination (i.e. prevailing wind direction or slope of terrain). In situ dose rate measurements of gamma emitting radionuclides should be used as a minimum to identify and delineate a pattern of elevated contamination. From this, a set of sampling sites can be identified as required by the sampling objectives. Consideration should also be given to the field of view of each measurement, the detector height above the ground and the radionuclides being measured.

In a typical in situ gamma spectrometry measurement, the detector is placed at 1 m above the soil surface. At this height, 85–90% of the gamma radiation detected originates from a round area with a radius of about 10 m from the detector. For typical soil conditions, radionuclides can be detected to a depth of about 30 cm. The effective area observed by this detector (>300 m^2) may in fact give a more representative picture of contamination than conventional sampling and analysis [2.44, 2.45].

Experience from the assessment of agriculture fields in the contaminated areas in Ukraine shows that detailed maps of contamination for each field were required rather than the spatially averaged data derived from the large scale maps after the accident at the Chernobyl nuclear power plant. Such individual field surveys were initiated in 1987 and continued until at least 1993 by means of dose rate measurements and soil sampling. The dose rate measurements were performed by walking along transects 50 m apart. Where the dose rate differed from the average value by less than 30%, the site was considered uniformly contaminated and soil samples were collected. In this way, the cartograms of contamination of each farm in Ukraine were created, which allowed the exclusion of the most contaminated land from agricultural use while other fields were derestricted for use.

In widespread contamination with sufficient gamma radiation emissions, aerial surveys can be a cost effective method for rapidly delineating and quantifying areas. Helicopters are used for low level work where maximum sensitivity is required. Positioning is generally accomplished with commercial navigation systems (e.g. GPS), which are also used to guide the pilot accurately along preselected routes. Gamma radiation, flight path, altitude and meteorological data are collected for real time or post-flight analysis. Gamma radiation data with spectral data overlaid on aerial photographs indicate the location of the contamination very accurately. For smaller scale work where aerial

surveys are not practical, data can be collected by vehicle mounted detectors, manually pushed carts, backpack systems and hand held detectors [2.44, 2.46].

Soil and vegetation sampling standards in Ukraine are from the Ministry of Agriculture and Rural Development. Dose rate measurements are carried out on a regular grid along tracks at a height of 1 m. Distances between the measurement points are not to exceed 100 m. The screened area is considered non-uniformly contaminated if the maximum deviation of the individual gamma dose rate from the average exceeds 30%. With inhomogeneous contamination, the examined area is divided into uniformly contaminated sub-areas, and sampling sites are chosen at each one. With homogeneous contamination, five sampling sites are selected where the gamma dose rate is closest to the mean value. One test site is located near the centre of the surveyed area and the other four at its periphery. Sampling locations need to meet the following requirements:

(a) It should be horizontal and flat, with homogeneous vegetation cover and without disturbance of the soil surface.
(b) It should be at a distance greater than twice the height of the nearest tree.
(c) The test sample location should be no closer than 20 m to the nearest roads or to places where there might be an accumulation or flushing of radioactive contamination in or from the soil.

Thus, a soil sampler or corer with a working surface area of at least 0.001 m^2 can screen the soil to a depth of 0.2 m. The distance between the point soil samples for a test site or between test sites should be at least 1 m. The composite soil sample of five points are selected using the envelope method, and the mass of the composite sample should be at least 1 kg. Radioactive contamination of vegetation is determined from a composite sample of individual plants. The locations for sampling vegetation at the site should be situated on a regular grid or distributed randomly, but not closer than 10 m from each other. Point samples cannot be selected at locations of topographic depressions within the microrelief and not closer than 20 m to roads or places of accumulation or flushing of radioactive contamination. Similarly, buildings and trees should be located away from the sampling site and at the distances greater than twice their height. Samples of grass are usually collected from an area of 1 m^2 and vegetation is cut at a height of 3–5 cm above the soil surface.

Several radiometric and geophysical in situ methods can be used to determine the sampling locations to establish the inventory of waste in trenches [2.47]. Techniques used include [2.48]:

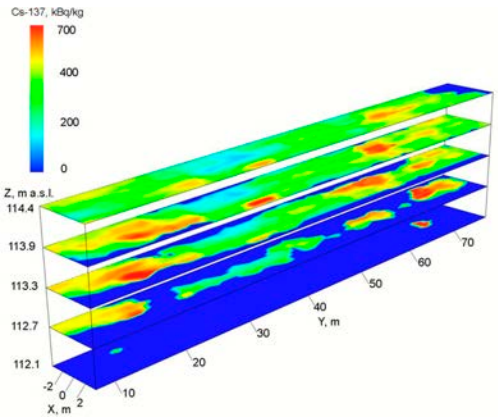
— Exposure dose rate measurements on a regular grid;
— Electromagnetic probing of the electrical conductivity of the soil;

— Gamma and beta ray logging of wells within the trench;
— Ground penetrating radar.

In a study on the Chernobyl nuclear power plant, Kashparov et al. [2.48] report:

> "As remote methods were not successful in determining the trench outline, an estimate of the radionuclide inventory was carried out by γ-ray logging of the trench body in a network of boreholes drilled with a hand auger. This method is rather difficult and labor-intensive, but it was successfully applied in the past in the Exclusion zone for characterization of shallow waste dumps and evaluation of the RAW [radioactive waste] inventories at the industrial site of the ChNPP.
>
> "For γ-ray logging, a specially designed field scintillation radiometer-probe (diameter of 55 mm and length of 20 cm) was used.... Approximately 130 holes were drilled to an average depth of about 2.5 m; the depth was limited by the water table. In the boreholes, measurements were performed every 10 cm, and the total number of measurements exceeded 2500."

The frequency distribution of the ^{137}Cs activity measurements in the trench is close to log-normal (the average quadratic deviation of the log of activity concentration is 0.2). The results from these trench investigations are presented in Fig. 2.22.



Source: Figure 7 of Ref. [2.48].

FIG. 2.22. Interpolated distribution of ^{137}Cs activity in the trench.

Similar approaches have also been adopted to characterize radium contaminated legacy sites. Gamma ray spectra recovered from boreholes, coupled with a Monte Carlo derived calibration and an artificial neural network approach, can be used to distinguish between point source radium contamination and homogenous radium contamination [2.49].

In situ measurements usually cannot fully replace sample collection and analysis, but it can be used in conjunction with sampling to reduce costs — there is a significant unit cost difference in price between in situ spectrometry and laboratory soil sample analysis due to the additional time and effort required for processing and measurement. There is some variability in this cost estimate, which is dependent on the radionuclide measured and the local factors such as cost of labour and analysis [2.45].

2.5.2. Geographic information system data

GIS has become an efficient tool for integrating data from a range of geospatial technologies, including navigation systems, digital cartography and mapped information, satellite pictures, remote sensing, web based resources, and open source and commercial software products. They have become a powerful tool for the design and optimization of environmental radioactivity monitoring and survey campaigns and for the effective presentation of the results. GIS technologies have made significant contributions to efficiency and productivity gains in sampling design, execution and reporting.

A GIS is a computer aided system for the capture, integration, storage, manipulation, analysis, application, management and presentation of maps, geographical data and mapped environmental variables (see the early work by Tomlinson [2.50], one of the first developers of GISs). In the description by Hengl [2.51]:

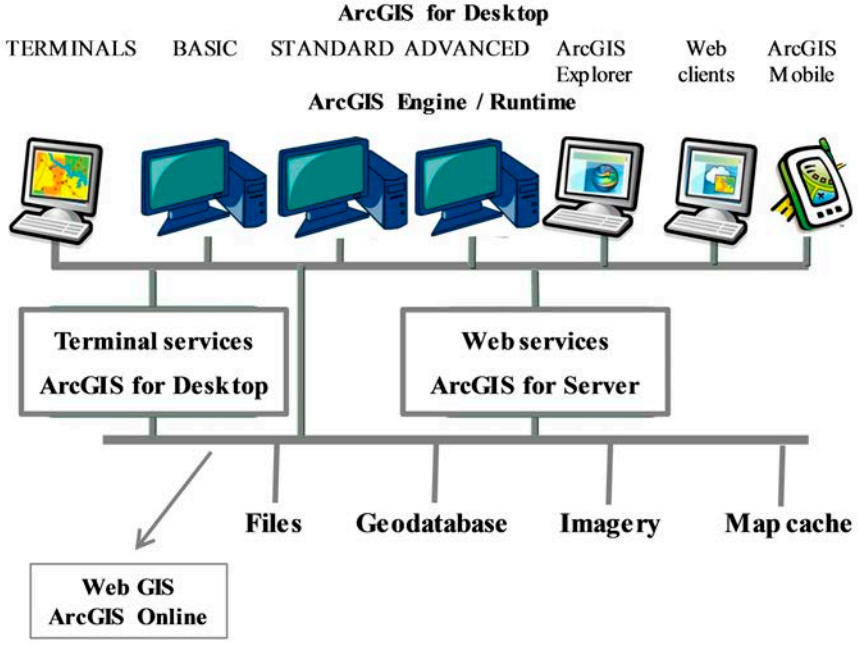
> "In summary, geostatistical mapping can be defined as **analytical production of maps by using field observations, auxiliary information and a computer program that calculates values at locations of interest** (a study area). It typically comprises the following five steps:
>
> (1.) design the sampling and data processing,
> (2.) collect field data and do laboratory analysis,
> (3.) analyse the points data and estimate the model,
> (4.) implement the model and evaluate its performance,
> (5.) produce and distribute the output geoinformation".

2.5.2.1. Establishment of a geographic information system

The basics of GIS design and implementation can be found in Ref. [2.52], and an example architecture is shown in Fig. 2.23. There are many open source and commercial GIS products and resources available. The file and data formats used by national authorities may need to be taken into account when selecting GIS applications to ensure compatibility.

2.5.2.2. Sampling plan preparation

When using a GIS, the generation and optimization of the sampling plan can be automated by geostatistical and multivariate modelling. Environmental factors that can affect the deposition and distribution of radionuclides (i.e. elevation, precipitation, temperature, soil type, land use, vegetation and historical data) can be selected as variables. A model matched to the environment can be prepared (see Section 2.5.2.4). After developing the sampling strategy, the sampling



Source: See http://wiki.gis.com/wiki/index.php/System_Design_Strategies_Preface

FIG. 2.23. Esri geographic information system.

points and plan can be generated. The preparation of the sampling plan can begin with collecting the relevant maps, mapped data, satellite images, in situ survey results, remote sensing data (i.e. gamma dose rate and meteorological data) and combining the collected data layers using the GIS resources. Most GIS applications have tools to support the development of sampling strategies and preparation of sampling plans. An example is the Esri ArcGIS 10.0[7]:

> "The Sampling Design Tool has two main functions: 1) to help select a sample from a population, and 2) to perform sample design analysis. When both of these functions are combined in an iterative manner, the tool effectively and simply achieves the goal of sample surveys — to obtain accurate, high-precision estimates of population metrics at a minimum of cost.
>
> "Key Features:
>
> - Spatial sampling: Sampling and incorporation of inherently spatial layers (e.g., benthic habitat maps, administrative boundaries), and evaluation of spatial issues (e.g., protected area effectiveness)
> - Scalable data requirements: Data requirements for sample selection can be as simple as a single polygon outlining the survey area or as complex as a stratified sample frame with historical sample data
> - Random selection — eliminates sampling biases.... A random seed number can be entered and a minimum distance between points can be specified.
> - Multiple sampling designs: Simple, stratified, and two-stage sampling designs
> - Sample unit-based sampling: Points or polygons are selected from a sample frame
> - Area-based sampling: Random points are generated within a polygon
> - Analysis: Previously collected data can be used to compute sample size requirements to efficiently allocate samples among strata in future surveys
> - Computations: Mean, standard error, confidence intervals for sample data and inferences of population parameters with known certainty".

[7] See www.arcgis.com/home/item.html?id=ecbe1fc44f35465f9dea42ef9b63e785

2.5.2.3. Use of a geographic information system

Typically, the implementation of a GIS approach for a field sampling campaign requires a portable computer with GPS and mobile GIS software for mapping real time data collection and transfer directly to GIS applications. All relevant information can be directly captured, stored, processed, mapped and shared in the field. Prerequisites for field sampling are that procedures, protocols, forms for sampling, recording and reporting relevant data, and sampling plan are all in place. Each sample and sample related information and photograph should be geotagged (latitude and longitude coordinates) and, where possible, information on altitude, bearing, distance, data accuracy and place names should be included.

2.5.2.4. Data analysis

For sample design analysis, it is important to prepare a model matched to the environment. Environmental variables include elevation, precipitation, temperature, soil type, land use and vegetation. After entering the measurement results a prediction map can be prepared. Hengl [2.51] finds:

> "From the statistical perspective, an environmental variable can be viewed as an information *signal* consisting of three components:
>
> $$Z(s) = Z^*(s) + \varepsilon'(s) + \varepsilon'' \quad (1.1.1)$$
>
> "where $Z^*(s)$ is the deterministic component, $\varepsilon'(s)$ is the spatially correlated random component and ε'' is the pure noise, usually the result of the measurement error. This model is in literature often referred to as the **universal model of variation**...."

Hengl [2.51] reports that there are many possibilities to interpolate point samples: "Spatial prediction models (algorithms) can be classified based on several aspects. Most importantly, they can be classified according to the amount of statistical analysis included".

2.5.2.5. Mechanical and empirical models[8]

Mechanical and empirical models use arbitrary or empirical model parameters. An estimate of the model error is not available, and strict assumptions

[8] This section is based on Ref. [2.51].

about the variability of a feature do not usually exist. The best known techniques that belong to this group include the following:

— Thiessen polygons;
— Inverse distance interpolation;
— Regression on coordinates;
— Splines.

2.5.2.6. Statistical (probability) models[9]

In statistical models, the parameters are estimated objectively, following probability theory. The predictions are accompanied with an estimate of the prediction error. However, a drawback is that the input dataset usually needs to satisfy strict statistical assumptions. There are at least four groups of statistical models:

— Kriging (geostatistics);
— Environmental correlation (e.g. regression based);
— Bayesian-based models (e.g. Bayesian Maximum Entropy);
— Mixed models (regression kriging).

2.5.2.7. Bayesian maximum entropy model

The Bayesian maximum entropy model is a general purpose predictive model that relies on environmental data layers with coordinates. In information theory, entropy is the average amount of information contained in each message (i.e. a sample drawn from a distribution) received and characterizes the uncertainty of the source. Stohlgren et al. [2.53] state:

> "Environmental monitoring programs must efficiently describe state shifts. We propose using maximum entropy modeling to select dissimilar sampling sites to capture environmental variability.... This approach can be widely used for cost-efficient selection of survey and monitoring sites.
>
> .....
>
> "Effective sampling sites would be expected to span important climatic, topographic, and environmental gradients, encompassing a broad range of vegetation types, soils, and geological substrates. Additional gradients, such

[9] This section is based on Ref. [2.51].

as disturbance regimes, land use change, and future climate changes might also be important to capture. ... And, designers are expected to distribute sample sites in a quantitative and objective (*i.e.*, a probabilistic) manner to later extrapolate results to the larger, un-sampled region with measurable estimates of uncertainty."

Hengl [2.51] groups the spatial prediction models as follows:

— Smoothing effect (whether or not the model smooths predictions at sampling locations):
— Exact effect (measured and estimated values coincide);
— Approximate effect (measured and estimated values do not have to coincide);
— Proximity effect (whether the model uses all sampling locations or only locations in proximity):
— Local effect (a local subsample; local models applicable);
— Global effect (all samples; the same model for the whole area);
— Convexity effect (whether the model makes predictions outside the data range);
— Convex effect (all predictions are within the range);
— Non-convex effect (some predictions might be outside the range);
— Support size (whether the model predicts at points or for blocks of land);
— Point based or punctual prediction models;
— Area based or block prediction models.

Hengl [2.51] finds that "spatial prediction can even be fully automated so that a user needs only to provide quality inputs and the system will select the most suitable technique" (see Fig. 2.24).

2.5.2.8. Buffering[10]

For safety reasons, a buffer zone around a potential source of contamination can be generated. A nuclear power plant might be buffered at distances of 10, 15, 25 and 30 km, forming multiple rings around the plant as part of an evacuation plan and following an incident, the contamination level is verified at the borders of these zones. In a GIS application, buffer zones can be easily and automatically generated. Buffering usually creates two areas: one within a specified distance to selected features and the other beyond them.

[10] This section is based on Ref. [2.54].

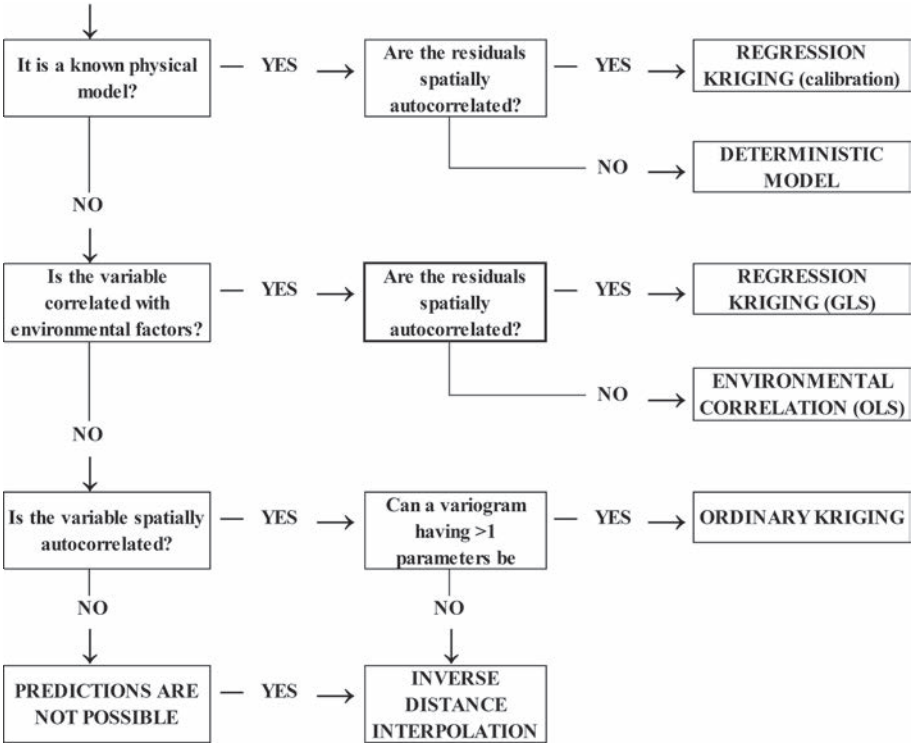
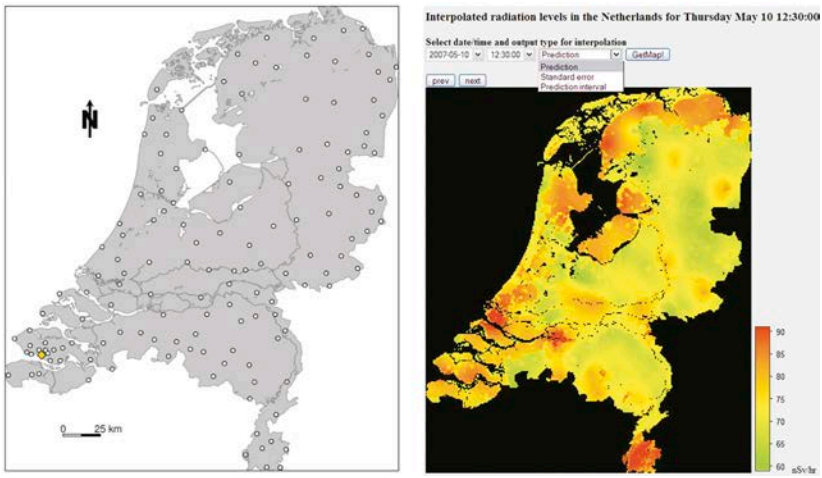


FIG. 2.24. Decision tree for selecting a suitable spatial prediction model [2.51].

2.5.2.9. Interpolation

A GIS can generate a map layer from a variable such as temperature and elevation. Using an interpolation method on the sample values yields predicted values for the whole site. In spatial interpolation, points with known values are used to estimate values of unknown points. For example, there are not enough evenly spread recording locations to make a gamma dose rate map for a country. However, spatial interpolation can estimate the dose rates at locations by using known dose rate readings at nearby recording stations (see Fig. 2.25). This is often called a statistical surface. The types of data which can be computed and mapped using interpolation include the following:

— Gamma dose rate;
— Results of in situ measurements;
— Laboratory results of samples;
— Elevation data;



Source: Figures 3 and 9 of Ref. [2.55].
Note: Left: Location of gamma dose rate monitoring stations of the National Radioactivity Monitoring Network. Diamond marks the Borselle nuclear power plant. Right: Map of the gamma dose rate created by interpolation of the monitoring data from the stations on the left side map. Client application running in real time inside a web browser.

FIG. 2.25. National Radioactivity Monitoring Network, the Netherlands.

— Precipitation;
— Snow accumulation;
— Water table;
— Population density.

2.5.3. Application of modelling approaches

Decision support systems and models, such as the real time on-line decision support system (RODOS) [2.56] for off-site emergency management in Europe, are important resources to solve complex environmental problems in the aftermath of a nuclear or radiological accident, including optimization of sampling programmes. Models use meteorological and monitoring data on radionuclides released into the atmosphere as input, and predict contamination deposition, distribution, dispersion and migration.

In the case of a nuclear accident in Europe, RODOS provides consistent and comprehensive information on the present and future radiological situation, the extent and the benefits and drawbacks of emergency actions and countermeasures, and methodological support for taking decisions on emergency response strategies [2.56]. Another example is ARGOS, “a software system to

support the emergency organization to make the best possible decisions in case of incidents involving atmospheric dispersion of hazardous CBRN-materials."[11] The ingestion dose model ECOSYS is integrated in the ARGOS and RODOS decision support systems for nuclear emergency management (see Ref. [2.57] for further information). These models can be used to predict outlines of contamination and hot spots and to optimize soil and vegetation sampling, including the number of samples, depth of sampling, surface area and volume for reliable measurement of activity.

2.6. SUMMARY

Successful monitoring campaigns and sampling strategies have clearly defined objectives that can be met with the most efficient deployment of equipment and resources. They are borne out of careful planning, which requires knowledge of:

— Geography and history of the site and surroundings;
— Use of the site and surroundings;
— Any external environmental influences acting upon the site and surroundings;
— Nature, form and frequency of site discharges;
— Wildlife and conservation designations;
— Stakeholder concerns;
— Available technology.

Sampling campaigns should ensure that the samples are representative and reproducible at a suitable monitoring frequency, while optimizing the sampling effort in proportion to the potential risk to the public and the environment. Monitoring programmes should also maximize the number of objectives that could be met with the samples collected and should be subject to regular review.

Soil and vegetation sampling are an important component of a monitoring campaign — either as the primary source of information or for the verification of other methodologies. Tables 2.4–2.6 are based on a UK regulatory interpretation of the IAEA Safety Standard Series No. RS-G-1.8, Environmental and Source Monitoring for Purposes of Radiation Protection [2.58], and provide examples of guidance on the location and frequency of monitoring for sampling soil, grass and crops for a number of objectives. Each table indicates whether the operator (O) or regulatory (R) programme should meet the objective set.

[11] See www.pdc-argos.com

TABLE 2.4. GUIDANCE IN THE UNITED KINGDOM ON WHERE TO SAMPLE SOIL AND THE FREQUENCY

Objectives	Data requirements	Location	Frequency	No. range/year	Total samples per year
Assess total impact on wildlife (e.g. dose) (R)	Bq/kg dry Wet/dry ratio	1–5 targeted to sensitive wildlife habitats and max. concentrations	Annually	1–5	
Assess impact on wildlife as an operator's performance measure (e.g. dose) (O)	Bq/kg dry Wet/dry ratio	1–5 targeted to sensitive wildlife habitats and max. concentrations	Annually	1–5	
Provide public and stakeholder reassurance (R)	Bq/kg dry Wet/dry ratio	1–5 targeted at population centres and/or max. concentrations	Annually to 3 yearly	1 per 3–5 years	Operator: 1–5 Regulator: 1–5 Should be part of a national programme for background survey every 10 years
Check/complementary monitoring (R, O)	Bq/kg dry Wet/dry ratio	At point of max. concentration	Annually to 3 yearly	1 per 1–3 years	
Assess background (very far field) (R)	Bq/kg dry Bq/m^2 Wet/dry ratio	1–2 remote locations or done as part of national programme for background (e.g. on 50 km national grid)	3–10 yearly	0–2 per 3 years	
Assess long term trends (R, O)	Bq/kg dry Wet/dry ratio	1–2 fixed locations, max. concentration, prevailing wind direction	Annually	1–2	
Understand/monitor behaviour of radionuclides in the environment (R, O)	Bq/kg dry Wet/dry ratio	1 location, max. concentration	Annually	1	

Source: Table 3 of Ref. [2.3].
Note: O — operator; R — regulator.

TABLE 2.5. GUIDANCE IN THE UNITED KINGDOM ON WHERE TO SAMPLE GRASS AND THE FREQUENCY

Objectives	Data requirements	Location	Frequency	No. range/ year	Total samples per year
Dose surrogate (R, O)	Bq/kg wet Wet/dry ratio	1 in the vicinity of where surrogate food type would have come from (e.g. milk, veg. or max. concentration)	Monthly to quarterly (during growing season assumed to be 8 months)	2–8	
Provide public and stakeholder reassurance (R)	Bq/kg wet Wet/dry ratio	1–5 targeted at population centres and/or max. concentrations	Quarterly to annually	1–20	
Check/complementary monitoring (R, O)	Bq/kg wet Wet/dry ratio	At point of max. concentration	Annually to 3 yearly	1 per 1–3 years	Operator: 2–12 (4–60 after incident) Regulator: 2–20 Should be part of a national programme for background every 10 years
Assess background (very far field) (R)	Bq/kg wet Bq/m^2 Wet/dry ratio	1–2 remote locations or done as part of national programme for background (e.g. on 50 km national grid)	Annually to 10 yearly	0–2	
Assess long term trends (R, O)	Bq/kg wet Bq/m^2 Wet/dry ratio	1–3 fixed locations, max. concentration prevailing wind directions	Quarterly to annually	1–12	
Detect abnormal, fugitive and unauthorized releases (indicator) (O)	Bq/kg wet Bq/m^2 Wet/dry ratio	1–5 (e.g. max. concentration)	Monthly to quarterly (after incident spot samples)	4–60	
Understand/monitor behaviour of radionuclides in the environment (R, O)	Bq/kg wet Bq/m^2 Wet/dry ratio	1 location, max. concentration	Annually	1	

Source: Table 3 of Ref. [2.3].
Note: O — operator; R — regulator.

TABLE 2.6. GUIDANCE IN THE UNITED KINGDOM ON WHERE TO SAMPLE CEREAL (CROPS) AND THE FREQUENCY

Objectives	Data requirements	Location	Frequency	No. range/ year	Total samples per year
Check/complementary monitoring (R, O)	Bq/kg wet	1–2 local producers and food types, 10% check	Annually to 3 yearly	1 per 3 years	Operator: 0–2 Regulator: 1–2
Assess background (very far field) (R)	Bq/kg wet	1–2 remote producers and food types or done as part of a national programme (e.g. from farms or markets)	Annually to 3 yearly	0–2	
Assess long term trends (R)	Bq/kg wet	1 producer and crop (highest concentration)	Annually at point of harvest	1	

Source: Table 3 of Ref. [2.3].
Note: O — operator; R — regulator.

The behaviour and fate of radionuclides can be affected by changing environmental conditions, such as prevailing wind direction and speed. Where such influences are likely, the sampling programme should also consider the collection of additional data to optimize the location of the sampling points, and the number will depend on the likely impact of a nuclear site and on the scale and heterogeneity of the site. A larger number of samples may be anticipated where doses to a representative person approach 0.02 mSv/a or greater. The number of samples to assess background at a national level is based on a 50 km sampling grid (see Section 8.6 for results in the United Kingdom).

The sampling for one objective will often satisfy the sampling requirements for a second objective, and this provides an opportunity for increasing sampling efficiency and avoiding double counting. Exceptions include sampling to establish background, impact on wildlife or detecting abnormal releases, depending on international monitoring requirements.

The frequency, timing and location of sampling will depend on the objectives of the monitoring programme, including:

— Detection of abnormal releases from nuclear sites;
— Frequency of licensed releases;
— Half-lives of target radionuclides;
— Rate of environmental change and frequency of environmental events;
— Seasonal events such as harvesting or site occupancy.

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Chapter 3

SAMPLING STRATEGIES FOR DIFFERENT CONTAMINATION SCENARIOS

The sampling programme should reflect the contamination scenario and be consistent with the objectives and purpose of the radiation impact assessment on people and the environment. The selection of sampling locations, times and techniques should fit the purpose and be justified based on the types of release, the target radionuclides and the exposure expected as a consequence (see Fig. 3.1) [3.1, 3.2].

Experience gained in assessing routine releases from nuclear facilities and mitigating consequences of radiation accidents (e.g. Chernobyl, Kyshtym and Fukushima) shows that the major uncertainty in the assessment of monitoring data and its impact on people and the environment is from soil and vegetation sampling. Other required steps such as sample measurements and data interpretation are associated with lower uncertainty.

3.1 SAMPLING FOR EMERGENCY RESPONSE MONITORING

3.1.1. Objectives, concepts and principles

The sampling programme for emergency response monitoring provides assistance to decision making. Sampling should therefore be performed in the minimum time to collect enough information to ensure representativeness of soil and vegetation samples. Typical objectives include:

— Assessing radionuclide distribution in terrestrial environments;
— Validating predictions of contamination from environmental models, enabling their development and reducing uncertainties;
— Mapping provisional contamination level estimates to identify areas where contamination of soil or vegetation exceeds intervention levels;
— Assessing public exposure.

Justification of the sampling programmes in the event of a nuclear or radiological emergency is a very challenging task and requires a high degree of flexibility. In an emergency, there are limited possibilities to compare environmental measurements with source monitoring results, since the amount of radioactive material released can only be estimated with large uncertainties,

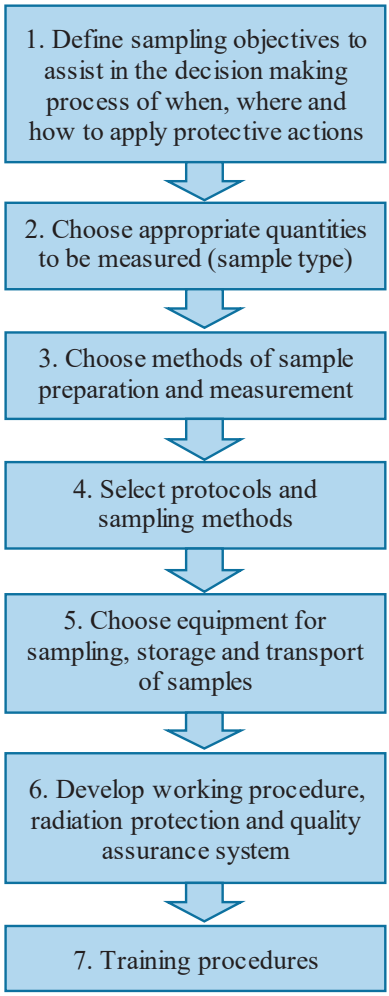

FIG. 3.1. Sampling strategy (general approach).

especially during the release phase. Environmental sampling should therefore provide data for supporting actions to mitigate radiological consequences.

The intensity and duration of the sampling activities depends on the severity of the emergency, lasting from a few days to years. In which season the accident happens is very important: outside the vegetation growth period, only a few types of vegetation will be affected by foliar contamination, which may significantly reduce the necessity for food monitoring [3.1].

As reported in Ref. [3.2], there will be few resources available immediately following a nuclear or radiological accident, so it is essential they be utilized effectively and efficiently until additional resources can be found. From the outset, meteorological data and model predictions should be used to determine areas affected by the release of the radioactive material. The priority for sampling depends on the land use (residential, agricultural, rural or commercial) and the types of industrial activity, public services and infrastructure. Additional protection for people, livestock, crops and water supplies can be necessary. Embargoes on the use of water and food and the maintenance or restoration of vital infrastructure should then be based on operational intervention levels (see also Ref. [3.3]).

Teams trained in soil and vegetation sampling will have to collaborate. Although they might not be specialists in radioanalytical techniques, operating in high dose rate or highly contaminated areas is likely. Hence, the teams need experience in radiological assessment techniques to enable them to monitor their own safety [3.2].

Sampling locations should give an overview of the immediate vicinity of the contamination source together with distal areas. In the early stages following an event, sampling and measurements should be performed in all directions, but predominantly in the main wind direction for an airborne release or downstream for an aquatic release. Locations will depend on the spatial distribution of the gamma dose rate in air in relation to the release of gamma emitting radionuclides. Monitoring is therefore focused on areas with potentially the highest contamination, while also taking account of land use. The external gamma dose rate can be measured directly, without soil and vegetation sampling. However, samples are required to establish intervention levels, on the basis of the irradiation dose values during various time intervals (evacuation, resettlement and temporary relocation), and to introduce restrictions for water and food consumption.

Estimates of radioactive plume dispersion based on computer simulations that take account of the source term and meteorological conditions can help to prioritize the monitoring effort, with priority given to populated areas [3.2]. Radiation protection of the sampling team should be a priority when planning sampling campaigns. Risk assessments and mitigation measures should take account of external and internal personnel irradiation at the time of sampling and be included in the dose assessment.

Understanding the behaviour of radionuclides with depth is important with increasing time following an accident. Samples should therefore include incremental sampling with depth at representative locations to evaluate the trends in the reduction of the external dose rate due to long term vertical migration of radionuclides within the soil.

3.1.2. Releases

Reference [3.2] reports:

"The composition of released radionuclides depends on the scenario of the reactor accident. Volatile radionuclides ^{131}I, ^{132}I, ^{133}I, ^{131}Te, ^{132}Te, ^{134}Cs, ^{137}Cs, ^{103}Ru and ^{106}Ru and noble gases have the highest probability for release. During the first days and weeks after an accident the highest portion of the dose comes from short lived radionuclides, like ^{132}I, ^{131}I, ^{132}Te, ^{103}Ru, ^{140}Ba and ^{141}Ce.[1] This must be taken into account when preparing a monitoring and sampling programme.

"The design of the emergency monitoring and sampling programme will be determined by the scale of the accident envisaged and the availability of qualified teams to respond to the radiological emergency."

Soil and vegetation sampling is carried out based on dose rate measurements only after the end of the release or plume passage: the measurement of radionuclide concentrations provides values for ground deposition and the necessary data to create contamination maps [3.2]. Radionuclide concentrations in vegetation provide important information on the form of fallout. Samples of grass, lichen and mosses are important indicators of fallout radionuclides. For emergency food restrictions, leafy vegetables (good indicator for plant food) should be collected on a daily basis. Samples from vegetables, fruit, grains and mushrooms should be collected at the time of harvest.

3.1.3. Selection of grid

The resolution of the sampling grid depends on the scale and magnitude of the contamination event, heterogeneity (occurrence of hot spots) and gradients of change, the landscape and climate. Radioactive contamination is determined by factors such as:

— Amount of release;
— Velocity of radioactive aerosol deposition;
— Height and durability of the radioactive substances released;
— Wind direction and velocity;
— Class of atmosphere stability;

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[1] As they decay, doses from ^{241}Am, ^{125}Sb, $^{134,137}Cs$, ^{144}Ce, ^{95}Nb, $^{238–240}Pu$, ^{106}Ru, ^{110m}Ag, $^{89,90}Sr$ and ^{95}Zr dominate.

— Intensity of sun irradiation;
— Occurrence of precipitates;
— Roughness of surface;
— Trees and herbage;
— Buildings;
— Mountains, hollows and bodies of water.

The sampling site and grid depend on the model forecasts for radionuclide dispersion and deposition following the event. Meteorological conditions are taken into account, along with gamma dose rate, beta particle flux density or density of area contamination. Following large scale contamination with gamma emitting radionuclides (e.g. Chernobyl and Fukushima nuclear power plants), surveys by air [3.4] and by car can be a cost effective method for rapidly delineating and quantifying the contaminated area. At the lower scale of contamination, cars [3.5] or pedestrian surveys can be used.

A regular radial grid of sampling locations along the axis of the trace of radioactive fallout against the source is generally used (e.g. cloud movement). The sampling grid resolution usually increases further from the source or axis of the radioactive trace. A reduction in resolution is therefore correlated with a reduction in radioactive contamination levels because of the dispersion and depletion of radioactive aerosols in a cloud. Humid radioactive fallout (i.e. fog, rain and snowfall) can lead to hot spots in the spatial distribution, and such effects should also be considered in the spatial resolution of the sampling grid. Ultimately, the sampling resolution should meet the goals of the sampling campaign and is balanced by the availability of resources.

3.1.4. Residential areas

Usually, the dose rate in residential areas is spatially highly variable due to the complex nature of land uses in a small area. Therefore, as stated in Section 2.5.1, dose rate measurements are carried out on a regular grid along the tracks at a height of 1 m. Distances between points are 50–100 m. The screened area is considered non-uniformly contaminated if the maximum deviation of the individual gamma dose rate from the average exceeds 30%. With inhomogeneous contamination, the examined area is divided into uniformly contaminated sub-areas, and sampling sites are chosen at each one. With homogeneous contamination, five sampling units are selected where the gamma dose rate is closest to the average to map initial fallout. One sample is located near the centre of the surveyed area and the other four at its periphery. Sample locations need to meet the following requirements:

(a) The sample location should be horizontal and flat, with homogeneous vegetation cover and without disturbance of the soil surface.
(b) The sample location should be at a distance greater than twice the height of the nearest tree.
(c) The test sample location should be no closer than 20 m to the nearest roads or to places where there might be an accumulation or flushing of radioactive contamination in or from the soil.

3.1.5. Agricultural and uncultivated areas

Each compartment of 1–10 ha (e.g. defined by a field boundary) is surveyed at a depth of 5 cm on uncultivated agricultural land (e.g. meadows, pastures and hayfields) and at least 20 cm in soils that have been ploughed since contamination. Actual sampling locations can be guided by the results of dose rates measurements. In areas relatively homogeneous in contamination, one composite sample should be sufficient. In case of recent non-homogeneous aerial contamination of agricultural crops, the period of an ecological half-life for the half-cleaning time from radioactive aerosols (~0–15 days) should be accounted for in the planning of vegetation surveys.

3.1.6. Forested areas

Immediately following radioactive fallout, most of the released radioactivity is located in the tree canopy. This will eventually contaminate the soil through washout and leaf litter on the surface. Soil samples of forested areas are important to assess the interception rate and prospective dose rates [3.6, 3.7]. Moreover, contamination on forest edges tends to be higher on the windward side of the point of radioactive release, compared with the centre of the forest or open grassland.

Soil samples should be collected from the top 5 cm of undisturbed soil, including leaf litter, and at points equidistant to the trees. Sample locations can be guided by dose rate measurements, but forest boundaries should also be considered. Sampling of wood and bark is carried out with special bores at a height of 1.3 m. Samples are collected from at least five trees with the median characteristic sizes (diameter and height of trunk) per sampling site.

3.1.7. Areas contaminated by liquid discharges

Surface water and groundwater contaminated with radionuclides used for irrigation or even melioration will contaminate soil and vegetation. Layer by layer characterization of soil samples may be required to understand the vertical

distribution of radionuclides in the impacted soil profile and to confirm the appropriate sampling strategy for contamination mapping and environmental management.

Discharges containing radioactive substances from nuclear facilities can be evaluated using soil and sediment cores. Dion et al. [3.8] assess the impact of the liquid effluent that leaked from the Savannah River Site, United States of America, by sampling sediment with 5 cm diameter plastic tubes to a depth of 36 cm, about 10–15 cm apart. The tubes were immediately capped, placed on ice and transported to the laboratory for further analysis. In a similar way, Standring et al. [3.9] evaluate the effect of liquid leakage from nuclear facilities in the Russian Federation by using a large box corer (50 cm × 50 cm × 60 cm), from which subcores were collected using plastic tubes (10 cm inner diameter) and then cut into 2 cm slices.

When assessing the distribution of radionuclides in contaminated vegetation from radionuclides in irrigation water, especially if applied from overhead, sample integrity needs to be maintained. This can differ significantly compared to vegetation contaminated by root uptake. In contrast, relatively small areas tend to be contaminated when radioactive waste is poured onto soil and vegetation. The contaminated area can be characterized by high spatial heterogeneity (distribution on surface and in a soil profile). In this case, soil sampling defines the contamination boundary, including radionuclides distributed vertically in the soil.

3.2. SAMPLING STRATEGIES FOR LEGACY SITES

3.2.1. Objectives, concepts and principles

Legacy sites include sites contaminated from many different scenarios, including [3.10]:

— Past activities such as discontinued mining and milling operations, and waste disposal;
— Accidents that cause contaminated materials to spread;
— Weapons tests;
— Inadequate management of radioactive material;
— Decommissioning of facilities.

Existing residual contamination needs to be identified, assessed and remediated where appropriate. Sites contaminated as a result of past activities or accidents can vary widely in terms of the following [3.11]:

— Composition and the physical and chemical form of radionuclides;
— Radionuclide activity concentrations in contaminated soil and vegetation;
— Ecosystems affected (e.g. urban, agricultural and forest);
— Environmental media affected (e.g. soil, surface water, groundwater or air);
— Distribution of contamination in the affected areas (i.e. environmental compartments).

The sampling strategy will need to provide the methodology for reducing the uncertainties and, at the same time, to increase confidence that the results meet the required remediation criteria. Soil and vegetation sampling programmes for legacy sites therefore verify compliance based on representative data on radionuclide activity concentrations. Typical objectives are:

— To provide information to determine areas with residual contamination;
— To determine on-site radiation levels to estimate long term radiation doses to the public and the environment;
— To determine the potential for off-site migration;
— To identify the required countermeasures or remedial actions to optimize environmental management of the area;
— To validate model predictions for dose assessment;
— To provide public reassurance.

Soil samples are collected no more than once a year. Samples of vegetables, fruit and grain should be selected at harvest. Terrestrial indicators such as grass should be collected each month when cattle are on pasture, or when mushrooms (and lichen and mosses) are being harvested. Samples of wood should be collected before felling trees. Additional sampling is required for identified contaminated areas to further define the areal extent and magnitude of contamination and to verify regulatory compliance. Planning the number, volume or mass of samples depends on the technical capacities and resources.

3.2.2. Residential areas

Sampling sites should reflect typical habits of the residential population. Samples should take account of the vertical activity distribution in the top 20 cm of the soil profile to establish dose conversion factors.

3.2.3. Agricultural areas and meadow

Soil samples should be collected to the depth of the vegetation routing zone (10 cm for fallow fields and 20 cm for cultivated land), which can also provide the data to predict vegetation contamination (using the transfer factor or concentration ratio). Soil samples can also be taken from agricultural soil to investigate the ingestion pathway. In these circumstances, it would also be appropriate to take samples of the crop from the same sampling location.

During the control of contaminated agricultural products, the edible parts of plant are collected for further treatment (i.e. washing and peeling) before being analysed for radionuclide concentrations. Grass and crop stems should be cut to a height of around 5 cm above the soil surface.

The differences in radionuclide uptake between plant species can exceed one or more orders of magnitude (e.g. for radiocaesium) and should be taken into account when designing the sampling programme. The impact of differing radioecological sensitivities of soils is often more important in explaining the spatial variation in radionuclide transfer to agricultural systems.

3.2.4. Forested areas

Contamination in forest soils can vary significantly with proximity to trees. Soil samples should therefore be collected at points equidistant from trees, on an undisturbed soil and to a depth of 20–40 cm. During soil sampling, the leaf litter is generally divided into several layers, depending on the state of decomposition and mineral content. Soil samples are not collected near the tree trunk because of possible contamination due to throughfall.

Post-depositional processes can lead to the redistribution of the radionuclides. For example, mushrooms can accumulate a significant amount of radiocaesium, which can lead to lateral redistribution and concentrations in locations which had previously contained the fruiting bodies of mushrooms (basidocarp). The sampling strategies chosen need to reflect this.

To estimate the contamination levels in wood, samples of merchantable wood (with and without bark) and firewood should be collected from at least three representative trees from the population for felling. Wood bore samples should be collected at a height of 1.3 m above the soil surface.

3.3. SAMPLING PROGRAMMES FOR COUNTRYWIDE MONITORING

3.3.1. Objectives, concepts and principles

In addition to providing information on national and regional trends in contamination levels, countrywide sampling programmes can also provide representative data:

— To assess baseline radionuclide activity concentrations in soil and vegetation for specific areas, representative landscapes, soils and plant species;
— To evaluate transboundary transfer and wide scale contamination;
— To assess the dynamics of radionuclide transfer from soil to vegetation for different regions and plant species;
— To identify temporal trends in radioactivity concentrations in soil and vegetation in areas potentially affected by radiation sources and nuclear facilities;
— To reassure the public.

The sampling programme should guarantee the identification of temporal trends in changes of radionuclide activity concentrations in soil and vegetation in areas potentially affected by radiation sources or nuclear facilities.

3.3.2. Selection of sampling areas

Countrywide sampling programmes consider terrestrial environments specific for the country and its regions. Sampling areas should thus be selected in major ecosystems specific for each region and samples be taken from major soil types and plant species [3.12]. The number of sampling areas and points should be:

— Optimized (see Chapter 2);
— Representative to support realistic dose assessments and to make judgements on contamination of major terrestrial environments;
— Large enough to assess trends in contamination levels for both regions and the whole country.

Sampling areas depend on the location of radiation sources and nuclear facilities and should be designed to assess transboundary radionuclide transfer. The sampling areas, points and their borders should be clearly defined with GPS to enable resampling and to establish time series trends in radioactivity.

3.3.3. Natural environments

Sampling areas of natural environments should include typical ecosystems for the region of interest (e.g. natural and semi-natural meadows, bog areas, forest) and dominant vegetation species and/or species characterized by elevated transfer of radionuclides or increased interception of radionuclides from the air (even if they are not dominant in the ecosystem). Once selected, all sampling areas are surveyed for the background density of long lived radionuclides in soil and vegetation (i.e. ^{137}Cs, ^{90}Sr, ^{226}Ra, ^{238}U and plutonium isotopes). The vegetation taxonomy at each sampling area is determined and documented. For natural grassland, sampling points should be within relatively homogeneously contaminated areas and similar composition of vegetation, with sampling units at around 50 m × 50 m. For each sampling unit, at least five conjugate samples of soil and vegetation are selected. Samples of vegetation need to be from the same period of growth and, if necessary, separated by botanical composition.

Soil cores help to determine the radionuclides distribution and the vertical sampling resolution (typically 1–5 cm). Vertical distribution of radionuclides can differ greatly, even at distances of less than 1 m. Therefore, at least three sampling points are needed, without mixing, so that activity concentrations and associated uncertainties can be established for each soil layer.

For forested areas, taxonomically homogeneous stands and radionuclide contamination are selected at a distance of more than 30 m from roads, active logging and areas with different characteristics and forest edges. Sampling units should be typical of the surrounding area, site conditions, quality class, tree age (over 5 years) and density. Sampling units are usually rectangular, with an aspect ratio of no more than 1:2 and at least 0.25 ha. Background density of radionuclide contamination of the leaf litter and mineral soil (20–40 cm deep) should be determined by a regular grid with a step of 5–10 m. In mountainous areas, samples are taken across the slope and altitude. Sampling stands at different heights is carried out from trees representative of the site. The number of trees should be 5–15 for pure stands and 3–5 for mixed stands.

For time series assessments, the sampling of soil and vegetation (e.g. shrubs, grasses, mosses and mushrooms) should be carried out at appropriate time periods (e.g. annually) at well defined locations and be separated by botanical composition.

3.3.4. Agricultural areas and meadow

Sampling areas on farmland should include field types and soils that are typical for the farming practice, geographical region and representative of the typical crop rotations. Samples should be taken annually at harvest sites to

calculate transfer factor values. The gamma dose rate should be measured at the same sampling point at heights of 1 m and 2–4 cm above the ground. At least ten soil samples are collected at equal distances on diagonals and in the centre of the sampling area. The samples are bulked to form a composite sample.

Vegetation at the site needs to be uniform and serried. The size of the sample area depends on the yield, but plots are usually 1 m^2. Any information on farming conditions, fertilizers, dose rates and specific treatments should also be recorded.

3.4. SAMPLING PROGRAMMES FOR ENVIRONMENTAL MONITORING AROUND NUCLEAR FACILITIES AND RADIATION SOURCES

3.4.1. Objectives, concepts and principles

Paragraph 4.1 of IAEA Safety Standards Series No. RS-G-1.8, Environmental and Source Monitoring for Purposes of Radiation Protection [3.1], defines the general objectives of any monitoring programme for the protection of the public and the environment as:

"(a) To verify compliance with authorized discharge limits and any other regulatory requirements concerning the impact on the public and the environment due to the normal operation of a practice or a source within a practice;
(b) To provide information and data for dose assessment purposes and to assess the exposure or potential exposure of critical groups and populations due to the presence of radioactive materials or radiation fields in the environment from the normal operation of a practice or a source within a practice and from accidents or past activities;
(c) To check the conditions of operation and the adequacy of controls on discharges from the source and to provide a warning of unusual or unforeseen conditions and, where appropriate, to trigger a special environmental monitoring programme."

Paragraph 4.2 of RS-G-1.8 [3.1] defines some subsidiary objectives as:

"(a) To provide information for the public;
(b) To maintain a continuing record of the impacts of an installation or a practice on environmental radionuclide levels;

(c) To check the predictions of environmental models so as to modify them as appropriate in order to reduce uncertainties in the dose assessment."

Paragraph 5.24(a) of RS-G-1.8 [3.1] defines the specific objectives of environmental monitoring as "To verify the results of source monitoring and the associated modelling to ensure that the predictions are consistent and that exposure limits are not exceeded". The sampling programme should also have the capability to detect both authorized discharges releases and incidental or accidental releases which otherwise might not have been detected [3.13].

3.4.2. Releases

A variety of radionuclides can be measured in areas affected by nuclear facilities. The sampling programme should be adapted to the composition of the effluent discharged from the facility. Volatile radionuclides $^{131–133}$I, ^{131,132}Te, ^{134,137}Cs, ^{103,106}Ru and noble gases could be detected, especially in some unplanned events at nuclear reactors. Nuclear activation products such as chromium, iron and zinc can be found in irrigated soil in surrounding areas. Natural radionuclide progeny of the uranium and thorium series can be found at facilities for mining, milling and uranium enrichment; ^{241}Am, ^{152,154}Eu, ^{237}Np and $^{239–241}$Pu can be of concern at reprocessing facilities [3.14]. These radionuclides behave quite differently in the environment, which should be taken into consideration when designing a sampling programme.

Sampling programmes for nuclear facilities include pre-operational studies and routine sampling. The main aim of pre-operational sampling is to determine the baseline activity concentrations in the environment and to be able to identify the impacts of the radionuclide discharges, if possible. This requirement is very important for nuclear facilities, but it is also an important component of environmental monitoring for other industries and practices. In particular, they can include different mines and milling activities handling naturally occurring radioactive material.

3.4.3. Selection of sampling sites

Reference [3.13] states:

"the following can be said to be relevant to environmental sampling for all facility types:

(a) Samples should always be drawn from such locations and in such a manner as to allow for the estimation of exposure of the representative person.
(b) Samples should be drawn from areas expected to experience maximum deposition as well as an area expected to receive no deposition to serve as a control (upwind or upstream from the facility).
(c) If possible, samples of different environmental matrices should be taken in such a manner that relationships can be established and trends observed (i.e. soil–plant–milk, aquatic plant–water).
(d) Samples should be taken from the same sampling points in order to ensure that comparable data are obtained and the long term impact of discharges can be observed."

Thus, Ref. [3.13] reports:

"In the design of an environmental monitoring programme, the environmental characteristics in the vicinity of a facility that need to be taken into account include, as appropriate:

(a) Prevailing wind direction;
(b) Meteorological variations;
(c) Current and future land use;
(d) Agricultural practices;
(e) Soil and hydrological properties."

The sampling sites should be selected at the pre-operational phase, and the pre-operational sampling programmes should be based on projected amounts of radionuclides that might be discharged during the subsequent operation of the facility and any potential exposure pathways. The sampling programme should begin a few years before a facility goes into operation and should be capable of providing data on baseline activity concentrations in different environmental compartments as well as their natural variations. Typical programmes include annual sampling of the upper layer of soil in areas which are:

— Most affected by discharges from a nuclear facility or another source of radionuclides;
— Highly vulnerable to radioactive contamination;
— Most sensitive to potential exposure of the public;
— Occupied by species indicators (i.e. some species accumulating more radionuclides than others).

Such sampling sites can be selected by modelling exposure pathways near a facility. Although most locations should be selected based on the above principles, sampling points should also represent the types of land use and soil to provide the information required for an emergency response. However, this sampling should be implemented only at the pre-operational phase.

Sampling during the operational period takes place every year. During which, the location of sampling areas, units and sites may change according to radioactive discharges and changes in land use near the facility. In situ gamma spectrometry can also be used to detect changes in soil concentrations and to optimize the number of sampling sites. However, soil and vegetation should be sampled from the same sampling points to obtain comparable data. Time dependent data is evaluated from the same sampling point to provide information on the long term accumulation of radionuclides in the environment. Depth incremental sampling of soil can be used to analyse vertical redistribution of radionuclides.

How much a facility contributes to the total concentration of radionuclides in the soil is often difficult to estimate because of radionuclides naturally present and fallout from the testing of nuclear weapons (e.g. ^{137}Cs and ^{90}Sr). Based on the radionuclide uptake, some species are good indicators of environmental contamination and can be used to analyse how much a facility contributes. Species such as lichen, mosses and pine trees (needles) can provide information which might not be detected in foodstuffs. Although they cannot be used to support dose assessments, they can provide valuable information on trends and environmental accumulation. Samples of agricultural soil and crops should be taken annually at harvest time, and leafy vegetables and grass each month during the growing season.

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Chapter 4

SAMPLING TECHNIQUES AND EQUIPMENT

This chapter presents sampling techniques for environmental radiological monitoring for soil, soil like materials and vegetation, and includes an overview of the types of equipment. The methods of sampling, preservation and storage, and the type of equipment used, depend on the following:

— Objectives of the investigation;
— Characteristics of the material;
— Sampling depth;
— Site specific conditions during sampling;
— Analytical methods applied;
— Sample type and quality required;
— Other relevant technical and organizational boundary conditions.

Vegetation samples are usually collected when available and depend on the season and spatial distribution. Any identification of the plant species covering the soil can be also useful. The investigation objectives determine whether the whole plant is taken or only the leaves, tuber, bulb, fruit or seeds. The area of the vegetation sampled is required to estimate transfer factors. Typical tools for sampling vegetation include sickles, scythes, secateurs, grass shears, trimmers, hedge clippers, pruning loppers or saws (see Fig. 4.1).

Techniques for sampling groundwater, surface water and the soil gas are out of the scope of this publication. Similarly, the extraction of pore water and soil gas from the pore volume of undisturbed soil samples is a pretreatment of the sample prior to lab analysis and therefore out of the scope of this publication.

The International Organization for Standardization (ISO) lists the following definitions for soil sampling (see Refs [4.1–4.6]):

— Topsoil, subsoil and other natural soil materials influenced by human activities such as relocated natural soils, degraded soils and contaminated (polluted) soils;
— Soils with a mixture of (artificial) materials (≤10wt%);
— Building debris or artificial soils (>10wt% of artificial materials);
— Mineral materials (tiles, concrete debris and certain industrial waste);
— Waste consisting of mineral soil or mineral materials (from stockpiles, tailings and other such industrial and mine waste);
— Sediments and dredged materials.

FIG. 4.1. Vegetation sampling equipment.

Construction materials (concrete, bricks, steel and cables) are out of the scope of this publication as well as all types of artificial material (i.e. intermediate products from industrial processes).

Soil investigation programmes — particularly those carried out at stockpile sites and waste dumps — may also require samples other than soil to be taken. ISO standards include the following:

— ISO 18400-102:2017, Soil Quality: Sampling, Part 102: Selection and Application of Sampling Techniques [4.2].
— ISO 18589-2:2007, Measurement of Radioactivity in the Environment: Soil, Part 2: Guidance for the Selection of the Sampling Strategy, Sampling and Pre-treatment of Samples [4.7], specifies general requirements based on ISO/IEC 17025, General Requirements for the Competence of Testing and Calibration Laboratories [4.8].

— ISO 22475, Geotechnical Investigation and Testing: Sampling Methods and Groundwater Measurements [4.9, 4.10], provides information on the required qualification of enterprises and personnel.

All vegetation growing on the soil surface and in the soil near the surface are included in the scope of this publication:

— Grasses;
— Bushes;
— Trees;
— Crops;
— Common weeds;
— Mushrooms and fungi;
— Lichen.

For radioactivity measurement, a relatively large amount of sample is usually required (from around 50 g to 2–3 kg dry sample), and the surface of the sample is important.

4.1. SAMPLE TYPES AND QUALITY

Samples types include undisturbed samples, disturbed samples from a specific location (and depth), or composite or pooled samples (individual samples mixed together from different locations in one pooled sample). Homogeneous samples can be split again into several homogeneous subsamples to enable simultaneous analysis by different types of laboratory test. ISO 18400-102:2017 [4.2] states[1]:

> "There are two basic types of sample which are collected for the purposes of investigating soil and ground conditions. These are:
>
> a) disturbed samples: samples obtained from the ground without any attempt to preserve the soil structure; ...
> b) undisturbed samples: samples obtained from the ground using a method designed to preserve the soil structure....
>
> "Disturbed samples are suitable for most purposes, except for some physical measurements, profiles and microbiological examinations for

[1] All citations from ISO 18400-102:2017 [4.2] are based on the wording used in the 2002 version.

which undisturbed samples may be required. Undisturbed samples should be collected if it is intended to determine the presence and concentration of volatile organic compounds, since disturbance will result in loss of these compounds to the atmosphere."

Disturbed soil samples can represent a range of grain sizes which can be distributed into a sorted sample. Composite samples are created by collecting samples from different locations (or depths) and combining them.

Vegetation samples are typically composite samples, and may be sorted according to species or plant part.

Five different sample quality classes are defined in Table 4.1 with respect to the degree of disturbance of the sample and the sampling method, where class 1 is an undisturbed sample and represents the original soil structure in situ. Table 4.1 also identifies the soil properties according to Ref. [4.11] that can be reliably determined. ISO 22475-1:2006, Part 1: Technical Principles for Execution [4.9], defines three sampling methods:

— Category A sampling methods can obtain soil samples of quality classes 1–5;
— Category B sampling methods can obtain soil samples of quality classes 3–5;
— Category C sampling methods can obtain soil samples of quality class 5 (completely disturbed samples).

TABLE 4.1. QUALITY CLASSES FOR LABORATORY TESTING

Soil properties	Quality class				
	1	2	3	4	5
Unchanged soil properties					
Particle size	X	X	X	X	
Water content	X	X	X		
Density, density index, permeability	X	X			
Compressibility, shear strength	X				
Properties which can be determined					
Sequence of layers	X	X	X	X	X
Boundaries of strata — broad	X	X	X	X	
Atterberg limits, particle density and organic content	X	X			
Water content	X	X	X	X	
Density, density index, porosity and penneability	X	X			
Compressibility and shear strength	X				

4.2. SELECTION OF SAMPLING TECHNIQUE AND EQUIPMENT

ISO 18400-102:2017 [4.2] states:

"The selection of sampling techniques should be guided by the following consecutive questions:

a) What are the soil characteristics of interest?
b) What type of sample is therefore required?
c) What amount of sample is needed for the investigations planned?
d) What precision of results is required and therefore what method can be used?
e) What is the accessibility of the sampling site?
f) What sampling depth must be reached?

"Additionally, costs, safety, availability of qualified staff, machinery or instruments, time and environmental aspects will lead to the final selection of the appropriate sampling technique."

Table 1 of ISO 18400-102:2017 [4.2] provides guidance on selecting appropriate sampling techniques. It provides information on manual methods, power driven methods and machine excavations, including information on sample sizes, achievable quality and sampling depth, suitability, and geotechnical boundary conditions and restrictions. The sampling technique has to be based on the proper characterization of the soil or subsoil layers to be sampled. ISO 14688, Geotechnical Investigation and Testing: Identification and Classification of Soil [4.12, 4.13], provides guidance on identifying and describing soils and selecting the correct sampling technique. It also provides principles for soil classification.

Sampling can be carried out using manual techniques (hand excavation, hand auger and corer samples), power driven (all types of drilling, including small diameter drilling, such as ram core soundings, and cone penetration testing) and mechanical excavations. To sample uniform surface layers of soil, ISO 18589-2:2007 [4.7] recommends a 20 cm square, 5 cm deep frame (see Fig. 4.2) or a 5 cm wide ring, 5 cm deep (good for incremental composite sampling).

FIG. 4.2. Sampling frame (adjustable depth).

ISO 18400-101:2017 [4.1] recommends[2] the following:

"Commonly, sampling strategies are employed which require samples to be taken either from identifiable soil horizons, or from specified depths (below ground surface)....

.....

"The sampling of soil for the determination of certain physical properties requires special consideration, since the accuracy and extrapolation of measured data relies on obtaining a sample which retains its *in situ* structural characteristics.

"In many circumstances it may be preferable to conduct measurements in the field, since the removal of even an undisturbed sample can change the continuity and characteristics of soil physical properties and lead to erroneous results.

[2] All citations from ISO 18400-101:2017 [4.1] are based on the wording used in the 2002 version.

> "However, certain measurements are not possible in the field. Others require specific field conditions, but the field situation can only be controlled to a very limited extent, ...
>
> "Differences and changes in soil structure affect the choice of sample size. Hence, a representative volume or minimum number of replicates shall be determined for each soil type to be studied.
>
> "The moisture status of the soil at sampling can influence physical measurements, e.g. hysteresis on rewetting can occur."

Sample consistency will often depend on water content, which affects storage and transport requirements. The required minimum size of a sample also depends on its physical properties (e.g. often by the grain size distribution of a soil sample). The recommendations in ISO 18400-101:2017 [4.1] can also be appropriate for investigating soil quality when the liquid phase of a soil sample is to be extracted or measured (see Refs [4.14–4.17] for samples of sediment and sludge).

Any soil sampling investigation involves some disturbance of the soil. When carrying out investigations on highly contaminated sites, consideration should be given to using probehole, borehole or other similar techniques rather than excavations in order to minimize and reduce problems due to exposure, disturbance and potential dispersal of the contamination. ISO 18400-101:2017 [4.1] states:

> "Biological soil investigations address a number of different questions related to what is happening to or caused by life forms in and on the soil, including both fauna and flora in the micro and macro ranges. ...
>
> "In some cases biological soil test procedures operate with fully artificial soils, but normally the major task of sampling is to choose a reliable soil or site to carry out the tests."

Fesenko et al. [4.18] report that the selection of proper sampling equipment and the related sampling procedures should ensure that the sample be representative of the sample type, providing sufficient sample mass for the selected laboratory measurement method and of the required sensitivity to ensure compliance with the set data quality requirements. Table 3 of ISO 22475-1:2006 [4.9] provides soil sampling techniques using samplers and indicates the sample quality classes that can be achieved by applying the respective sampling method.

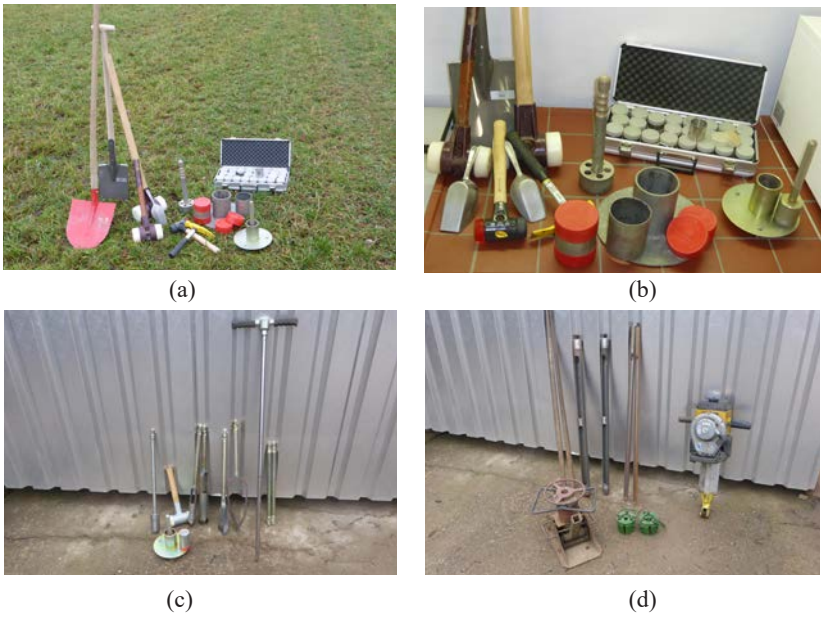
Tables 4.2 and 4.3 provide information on selected soil sampling equipment typically used for radiological monitoring purposes [4.18]. The applications, advantages and disadvantages can be used as additional guidance when selecting the appropriate equipment. Typical hand operated equipment and sample types obtained for soil are shown in Figs 4.3–4.5. The Fine Increment Soil Collector, developed by Mabit et al. [4.19], can be used to determine the vertical activity distribution for radionuclides with some precision (see Fig. 4.6).

TABLE 4.2. SOIL SAMPLING EQUIPMENT

Equipment	Application	Comments
Scoop, spatula	Soft surface soil	Inexpensive, easy to use and decontaminate, difficult to use in dry and rocky soil
Topsoil template	Surface up to 5 cm	Easy to use and decontaminate, defined sampling depth and area, difficult to use on rocky surface
Bulb planter	Soft surface soils	Inexpensive, easy to use and decontaminate
Soil coring device	Soils up to 60 cm, different diameters	Relatively easy to use, preserves soil core, not suitable for sandy soils, limited depth capability, can be difficult to remove and cut cores for profile information
Box coring device	Soils up to 50 cm	Preserves information of sampling profile, defined collection volume and sampling depth, difficult to use
Split spoon sampler	Soil to bedrock up to 3 m	Excellent depth range, soil profile information, can be used in conjunction with drill rig, suitable for deep cores
Spiral auger	Soil up to 1.5 m	Easy to use, suitable for hard soil, mix layers
Bucket auger	Soft soil up to 3 m	Easy to use, good depth range, uniform diameter and sampling volume, may disrupt soil horizons > 15 cm
Hand or power operated auger	Soil 0.15–4.5 m	Good depth range (depends on extension length and material), generally used in conjunction with bucket auger, destroys core, difficult to use if deep cores are sampled
Subsoil probe, linear sampler	Soft to medium hard soils up to 7 m	Good depth range, undisturbed soil, profile information possible
Power operated push corer	Flexible depths, depends on soil type	Good depth range, undisturbed soil, profile information possible
Ram core sounding with split tube	Flexible depths, depends on soil type (up to 8 m achievable)	Easy to use, good depth range, uniform diameter and sampling volume, may disrupt soil horizons

TABLE 4.3. SEDIMENT SAMPLING EQUIPMENT

Equipment	Application	Comments
Grab sampler	Sediment surface up to 30 cm below surface	Disturbed sample, many types available
Gravity corer	Sediment core up to 180 cm below surface	Many types available, limited penetration depth for low weight corers, not suitable for soft soils and sediments
Piston corer	Sediment core	Many types available, suitable for short (<1 m) and longer cores (up to 30 m) in fine grained unconsolidated soils and sediments Keeps profile information, deeper coring needs hydraulic cranes
Freeze corer	Sediment or soil with high water content up to 1 m	Keeps profile information, cooling and dry ice needed during collection and for transport
Corer sampler with seal mechanism (pneumatic or mechanical seal)	Sediment or soil with high water content (pulpy or liquid consistency) Depending on soil properties up to > 2.0 m	Suitable for cohesive sediments of pulpy or liquid consistency, keeps profile information if properly transported (if needed, in vertical orientation)
Cone penetration testing with sampling device	In loose sandy soils and cohesive soils with weak or pulpy consistency, up to 50 m possible	Sample from small individual layer, slightly disturbed sample, continuous measurement of other parameters with depth possible (i.e. electrical conductivity, geophysical parameters, indirect determination of the soil type and soil properties possible)



(a) (b)

(c) (d)

Note: (a) Shovel, spade and cylinder tube samplers, including cylinder samples of two sizes. (b) Scoops, spade and two sizes of cylinder tube sampling equipment (topsoil templates). (c) Soil samplers for maximum depth (ca. 1 m): soil core sampling device, cylinder tube sampler (topsoil template) with hammer, two bucket samplers, two digging devices, and an extension rod with grab handles. (d) Hand operated ram core sounding with split tube sampling device, motor driven hammer, split spoon sampling rod, extension rods and hand operated withdrawing equipment.

FIG. 4.3. Typical hand operated soil sampling equipment.

FIG. 4.4. Hand excavation of disturbed soil sample and measurement of in situ natural density using the balloon method. (Courtesy of Department Mining Remediation/Geotechnics, Wismut).

FIG. 4.5. Undisturbed liner sample (100 mm in diameter and 2 m long) of soft tailings obtained below water table using hand operated corer sampling equipment (0.2 m deep).

(a) (b)

Source: Figures 1 and 2 of Ref. [4.19].
Note: a — cover; b — soil sediment collector ring; c — stainless steel cylinder; d — graduated scale; e — screw thread system.

FIG. 4.6. Fine Increment Soil Collector.

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Chapter 5

SAMPLE PREPARATION AND PROCESSING

5.1. GENERAL

This chapter presents methods in radiological monitoring for the preparation and processing of samples of soil, soil like material and vegetation. It provides information on sample packaging, transport, storage and preservation, sample pretreatment in advance of laboratory measurements, chain of custody and documentation. Sample processing for laboratory tests for chemical components and/or specific radionuclides is out of the scope of this publication. The relevant International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) standards include the following:

(a) ISO 18400-101:2017, Soil Quality: Sampling, Part 101: Framework for the Preparation and Application of a Sampling Plan [5.1], provides general information on laboratory preservation, handling and containerization, labelling and transport of soil samples.
(b) ISO 18589-2:2007, Measurement of Radioactivity in the Environment: Soil, Part 2: Guidance for the Selection of the Sampling Strategy, Sampling and Pre-treatment of Samples [5.2], provides detailed information on measuring radiological parameters.
(c) ISO 9000:2015, Quality Management Systems: Fundamentals and Vocabulary [5.3], and ISO 9001:2015, Quality Management Systems: Requirements [5.4], contain guidelines which ISO 18400-101:2017 [5.1] recommends be followed as far as practicable.
(d) ISO/IEC 17025:2017, General Requirements for the Competence of Testing and Calibration Laboratories [5.5], contains requirements which organizations offering analytical services should follow.
(e) ISO 5667-15:2009, Water Quality: Sampling, Part 15: Guidance on the Preservation and Handling of Sludge and Sediment Samples [5.6].

Fesenko et al. [5.7] report that to avoid bias introduced by sample processing, preparation and measurements, it is essential to harmonize the procedures prior to measuring. Only validated or verified procedures are to be used, and written procedures should be available to all laboratories assisting in sample preparation and measurement. This will ensure that all data used for

characterization are comparable, have the same quality and can be combined with each other. ISO 18400-101:2017 [5.1] states[1]:

> "Samples of soils and related materials are liable to change to differing extents as a result of physical, chemical or biological reactions which may take place between the time of sampling and the analysis. This is especially true of soils contaminated with volatile constituents.
>
> .....
>
> "The extent of these reactions is a function of the chemical and biological natures of the sample, its temperature, its exposure to light, the nature of the container in which it is placed, the time between sampling and analysis, the conditions (e.g. rest or agitation during transport) to which it is submitted, seasonal conditions, etc.
>
> "It must be emphasized, moreover, that these variations are often sufficiently rapid so as to modify the sample considerably within several hours. ...
>
> .....
>
> "The addition of chemical preservatives or stabilizing agents is not a common practice for soil sampling. This is because a single soil sample is usually used for a large number of different determinations, and moreover has to undergo preparation (drying, milling, etc.) during which unwanted and unquantifiable reactions of the preservatives may occur.
>
> "If in special cases it is necessary to preserve samples, a method that does not introduce unacceptable contamination should be chosen.
>
> "Broadly, stability of samples can be considered in three classes:
>
> a) samples in which the contaminant(s) is/are stable;
> b) samples in which the contaminant(s) is/are unstable but stability can be achieved by a preservation method;
> c) samples in which the contaminant(s) is/are unstable and cannot be readily stabilized."

[1] All citations from ISO 18400-101:2017 [5.1] are based on the wording used in the 2002 version.

Particularly for unstable contaminants, special measures may have to be introduced, such as in situ or on-site flash freezing in liquid nitrogen or the adoption of in situ analysis or off-site analysis shortly following sampling [5.1].

5.2. SAMPLE PREPARATION

Sample preparation depends on the investigation methods and the types of sample matrix. It can be carried out on-site or off-site and includes splitting, sorting, sieving, mixing and homogenization of samples. The different types of solid sample typically include the following:

(a) Natural soil sampled from soil horizons, subsoil layers and mineral soil;
(b) Anthropogenic soils, such as construction debris or soils mixed with other materials;
(c) Earthen (construction) materials, such as gravel, sand, split, crushed rock and macadam;
(d) Waste and residues, such as mineral waste, mine waste, waste rock material, and industrial and processing waste (e.g. tailings);
(e) Sediment samples, such as soil samples taken below the water table from lakes, ponds, riverbeds and creeks.

Undisturbed soil samples are usually packed without further sample preparation in the field. Depending on the investigation, foreign materials (e.g. stones, leaves or wood) gathered with the sample are collected and sorted. Samples are to be sufficiently protected against adverse impacts during transport. Disturbed soil samples do not usually require sample treatment.

With respect to radiological monitoring, ISO 18589-2:2007 [5.2] states that in the preparation of sorted samples:

> "The increments from the same sampling unit are placed in a clean container or plastic bag. The resulting composite sample is spread out over a clean, level, inert surface and mixed thoroughly using a shovel or other suitable tool. During the operation, the clods are broken up and the coarse elements larger than 2 cm are removed (or collected separately, depending on the objective of the study) in order to obtain a sorted sample.
>
> "For certain studies, the respective proportion of coarse elements compared to the mass of the sampled soil should be estimated and their radioactive characteristics measured. The petrographic nature and apparent porosity of the sample should be noted. ...

"The quartering technique (see ISO 11464 [5.8]) may be used to split the sorted sample to obtain a subsample of approximately 1 kg of dry matter.

"All sorted samples sent to the laboratory shall be identified and a sample sheet drawn up. ...

.....

"For a soil profile, the samples taken from different soil horizons shall not be mixed, unless otherwise required, and increments shall not be combined or undergo any homogenization or clod-crushing treatment when investigating radionuclides in the form of volatile compounds."

The preparation of vegetation samples on-site or off-site depends on the investigation. If certain parts of a plant or specific species are required, these have to be separated from the rest of the sample.

5.3. TRANSPORT

Samples need to be transported safely with regard to workers, the public and the environment. For soil and other material classified as radioactive or radioactively contaminated, specific transport rules and precautionary measures can apply and permits and accompanying transport documents may be required. The transport is not to cause changes to the physical, chemical, radiological or biological properties of the samples, and the transport method needs to be chosen carefully (car, lorry, train, ship or plane). ISO 18589-2:2007 [5.2] states:

"Transport and storage conditions shall be such as to avoid all contamination of the material. The transport and preservation temperatures of the samples should be specified...where necessary, in the test report.

"The following are particularly recommended:

— to avoid any warming of the sample during transport...;
— .....
— to limit the time between sampling and radioactive analyses, especially when researching radionuclides with short half-lives;
— to take particular precautions in the case of the investigation of volatile, organically bound or highly soluble radionuclides".

ISO 18400-101:2017 [5.1] and ISO 18400-102:2017, Part 102: Selection and Application of Sampling Techniques [5.9], provide general information on the transport and storage of samples, and guidance on measuring radioactivity in the environment is provided in ISO 18589-2:2007 [5.2]. Sample containers need to be physically and chemically stable and not react with the sample material. ISO 18400-102:2017 [5.9] states[2]:

> "When sampling areas are suspected of contamination, it is essential to ensure that the material of the sample container is such that the sample remains representative. ...
>
> "Sample containers should always be filled and sealed so that there is minimum free air space."

Table 2 of ISO 18400-102:2017 [5.9] provides guidance on the suitability of different sample containers. ISO 18400-101:2017 [5.1] states:

> "Containers holding samples should be protected and sealed in such a way that the samples do not deteriorate or lose any part of their content during transport. Packaging should protect the containers from possible external contamination, particularly near the opening, and should not itself be a source of contamination.
>
> "Most of the analytical procedures used in chemical soil analysis recommend that soil samples be taken to the laboratory immediately after sampling, but in some cases a range of time is given within which the sample should arrive in the laboratory.
>
> "Soil samples should be kept cool and dark during transportation and storage.
>
> "Cooling or freezing procedures can be applied to samples to increase the time period available for transport and storage. A cooling temperature of 4°C ± 2°C has been found suitable for many applications. But cooling and freezing procedures should only be used in consultation with the analytical laboratory. ...

[2] All citations from ISO 18400-102:2017 [5.9] are based on the wording used in the 2002 version.

"Light-sensitive soil constituents require storage in darkness or, at least, in light-absorbent containers.

"Vibration or other damage to undisturbed samples should be avoided in order to maintain the original structure during transport.

"Disturbed samples, and especially non-cohesive very dry soils, tend to separate into different particle fractions during transportation. In such cases, the soil material should be re-homogenized before further pretreatment and analysis.

"Any national regulations regarding the packaging and transport of hazardous materials should be observed."

5.4. STORAGE

ISO 18400-102:2017 [5.9] states:

"Cooling and storage of soil samples at below 5°C is recommended, as this helps to slow down any change or deterioration in the sample. This can be effectively achieved on site by the use of cold boxes which can also be used for transporting samples to the receiving laboratory.

.....

"Care shall be taken, especially in hot and humid climates, if cooling causes condensation of soil gas moisture that might leach the sample."

The construction and operation of the storage facility may require a permit, and the sample properties and the amount of material stored will need to meet technical and legal requirements; in particular, if the samples are toxic, radioactive or contain volatile or highly soluble substances of concern.

5.5. PRETREATMENT OF SAMPLES

5.5.1. Pretreatment of soil samples and other solids samples

Table 5.1 provides an overview of typical laboratory equipment, the respective type of sample preparation and the types of soil matrix [5.7]. Equipment for sample preparation and pretreatment is shown in Figs 5.1–5.5.

TABLE 5.1. TYPICAL EQUIPMENT FOR CRUSHING, MILLING, MIXING AND HOMOGENIZATION [5.7]

Equipment	Type of preparation	Matrix
Jaw crusher	Preliminary size reduction by pressure	Hard matrices (e.g. soils, building material)
Ball mill	Reduction of particle size by impact and friction	Soils, sediments, vegetation Use depends on ball and container material
Cross and rotor mill	Preliminary size reduction and fine grinding	All dried matrices Depends on equipment material Can be combined with sieving
Centrifugal mill	Reduction of particle size by impact and shearing	Soft and fibrous materials
Disk mill	Reduction of particle size by pressure and friction	All soft and middle hard matrixes Depends on equipment material If combined with cooling, can be used for volatile matrices
Cutting mills, household and restaurant blenders	Preliminary size reduction by pressure, wet blending allows homogenization	Vegetation or soft matrices
Mortar grinder	Fine grinding by pressure and friction	Depends on equipment and material
Rotation mixer	Homogenization, tumbling axis	All matrices with smaller particle size
V-blender	Homogenization by splitting and remixing	All matrices with smaller particle size

FIG. 5.1. Sample quartering device.

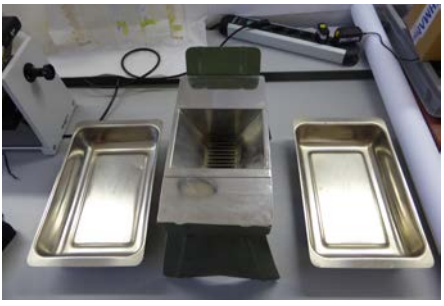


FIG. 5.2. Soil sample splitting device.

FIG. 5.3. Equipment for homogenization: jaw crusher (left) and mixer (right).

FIG. 5.4. Sieving equipment (grid size 2–32 mm).

(a)

(c)

(b)

(d)

FIG. 5.5. Sample preparation tools: (a) hand operated wet sieves; (b) disk mill for pulverization; (c) oscillating disk mill; and (d) disk mill grinding elements

5.5.2. Pretreatment of soil samples with respect to measurement of radioactivity in soil

ISO 18589-2:2007 [5.2] states:

"**8.1 Principle**

"The physical processing of soil laboratory samples to measure radioactive nuclides requires drying, crushing, sieving and homogenizing steps to be carried out.

"NOTE Before any pre-treatment, a preliminary analysis of the laboratory sample by gamma spectrometry can allow detection of volatile radionuclides and, if so, the selection of the adequate pre-treatment procedure compatible with the quantification of their activity.

"**8.2 Laboratory equipment**

"The following equipment is necessary to carry out the pre-treatment of the laboratory sample:

— a ventilated drying room or drying cabinet with a temperature of (40 ± 5)°C;
— a heated, ventilated oven with a temperature of (105 ± 10)°C;
— equipment for the reduction of clods, possibly combined with a sieve: pestle and mortar, pounder, grinder, crusher or grip breaker;
— a sieve with a 2 mm mesh size;
— a sieve with a 200 μm mesh size;
— a metal or plastic tray with raised edges;
— a mixer or ball mill;
— freeze-drying equipment (when appropriate).

"**8.3 Procedure**

"With consideration for the composition of the test sample, the following steps shall be carried out:

— Weigh the laboratory sample.
— Spread a thin layer of 1 cm to 2 cm of the entire initial test sample onto flat containers and manually break up the sample using a suitable instrument.

— Remove all remaining plant parts (tufts of grass, roots, etc.).
— Leave the sample to dry at ambient temperature or in a ventilated cabinet heated to a temperature less than 40°C for 24 h to 48 h, according to the moisture in the sample.
— Break up the remaining clods of earth with suitable equipment.
— Separate the fine earth from the coarse elements using a 2 mm sieve and note their masses.
— Dry the powder at (105 ± 10)°C to a constant weight. When measuring volatile radionuclides, it is better to freeze-dry the sample or dry it to a maximum fixed temperature of (40 ± 5)°C.
— Crush with a mortar, mixer or a ball mill.
— Sieve using a 200 μm sieve, then homogenize the powder obtained.
— Repeat the crushing and sieving steps until the entire sample has been processed.
— Weigh the total powder and the unsieved material, then discard. Record the mass obtained. The powder part constitutes the test sample.

"The above steps should be carried out in accordance with the procedures in ISO 11465 [5.10] with respect to the drying temperatures and grain sizes. Any modification of the above procedure shall be justified and shall be included in the test report."

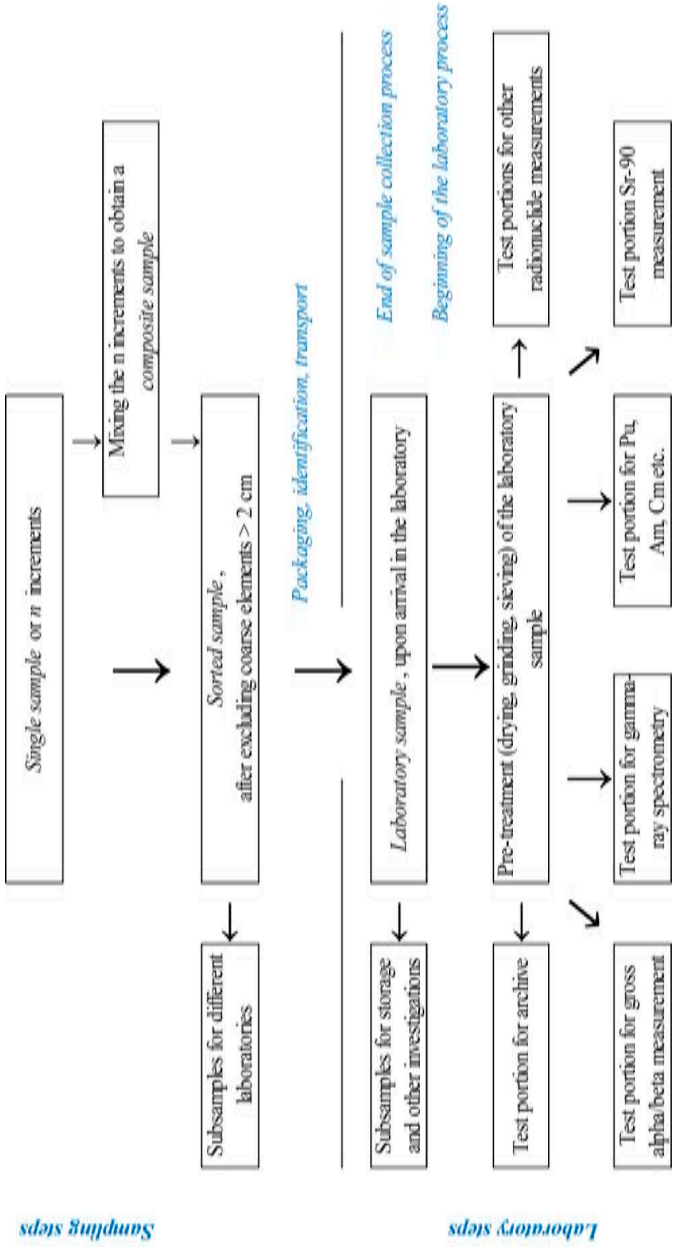
Figure 5.6 shows the evolution of the sample characteristics, divided into sampling steps (including sample preparation in the field) and laboratory steps (including the sample pretreatment before laboratory analysis). Equipment for weighing and drying of samples is shown in Fig. 5.7.

5.5.3. Pretreatment of vegetation samples

The pretreatment of vegetation samples depends on the investigation and can involve separating the required parts from the rest of the plant and removing soil and other materials. Physical pretreatment methods also include cutting, crushing, milling and drying. Chemical pretreatment is beyond the scope of this publication.

Nearly all laboratory analysis techniques of vegetation samples require further preparation before measurement, such as cutting, washing, peeling, milling, homogenizing, drying and ashing. The different types of equipment include scissors, knives, mills (ball, rotor, centrifugal, disk and cutting), rotation mixers and blenders [5.7].

Care needs to be taken during transport, drying and ashing not to lose the radionuclide of interest through volatilization. This applies specifically to iodine



Source: Figure B.1 of ISO 18589-2:2007 [5.2].

FIG. 5.6. Evolution of the sample characteristics from the sampling site to the laboratory.

(a)

(b)

(c)

(d)

FIG. 5.7. Equipment for weighing and drying of samples: (a) drying oven including balance for continuous weighing; (b) drying oven cabinet; (c) electronic balance; (d) standard weight (1 kg) for regular calibration.

(at room temperature), tritium (>100°C) and caesium (>400°C), and special pretreatment and preparation conditions might be necessary. The influence of the chemical form (e.g. anion or organic species) on the evaporation temperature of the radionuclide may be significant, and wet ashing with nitric acid or peroxide can reduce losses. The selection of drying and ashing temperature can be critical for the data quality and interpretation of the results and needs to be harmonized for all analysing laboratories [5.7].

5.6. CHAIN OF CUSTODY

A chain of custody continually documents each individual sample — right from the moment of sampling through all work steps of sample preparation, packing, transport, storage, analysis until the final disposal of any remaining sample material. National regulations need to be observed during the process.

At all times, the sample has to be under control of the person responsible. The chain of custody is to be documented in accordance with proper quality assurance and quality control procedures. Any relevant incidents that might have affected the sample properties during the process also have to be documented by the person responsible. Best practice is to include the chain of custody information in the final report.

5.7. DOCUMENTATION

5.7.1. Recorded information

ISO 18589-2:2007 [5.2] states:

> "All steps and procedures carried out to establish the radioactivity of soil samples shall be completely traceable as specified in ISO/IEC 17025 [5.5]. This implies a complete documentation of the sampling strategy, plan chosen, the sampling operations performed and the chain of custody of the sample preparation.
>
> "Sheets detailing the sampling and laboratory steps shall be recorded. Each such record shall be dated and signed by a responsible person to attest the correctness of the results. Any relevant information recorded during the different steps described in this part of ISO 18589 [5.2] likely to have affected the results should be mentioned in the final test report.

"Records of all relevant information on the measuring equipment needed for the confirmation process of a result shall be kept. These records shall demonstrate that each item of the measuring equipment (balance, oven temperature, etc.) satisfies the metrological requirements specified within the confirmation process for the equipment. Calibration certificates or verification reports and other relevant information shall be available."

5.7.2. Labelling

ISO 18400-101:2017 [5.1] states:

"Once a sample is obtained it should be clearly and unmistakably marked. Normally, a containerized sample should have a label having all the required information on it. This can be done, for example, by either using adhesive labels, writing the information directly on the container, or putting the label inside the container with the sample. ... Labels should be short and simple, to avoid mistakes arising in transcribing numbers.

"It is recommended that at least the sample number should be placed on both the container and the lid to avoid undesired mix-up of containers and lids. The sample number should not be placed only on the lid.

.....

"Before samples are dispatched and on receipt in the laboratory, a check should be made that sample numbers on the container and on the lid can be correlated with the respective sampling report."

ISO 18589-2:2007 [5.2] states:

"**7.3 Identification and packaging of samples**

"Each sample shall be packed in a container that does not react with the soil, is clean and carefully sealed to avoid loss of the contents or exposure to external agents (infiltration of water, dust, etc.).

"The identification label shall be attached to the outside of the packaging.

"**7.3.1. Sample identification**

"The label of the container shall identify each sample and contain the following information:

— code identifying the sample, the sampling area and the sampling unit;
— date of sampling;
— additional information, such as the depth and thickness of the soil horizon sampled, may be added."

If the sample is undisturbed, the correct orientation of the sample (i.e. top and bottom) should be clearly marked on the label or the container. ISO 18400-102:2017 [5.9] states:

"The labels used should be resistant to external influences on the site (rain, contamination) and to future treatment (abrasions, handling, chemicals). The labels should be large enough to contain all relevant information in a legible form."

5.7.3. Sample sheet and sample recording

ISO 18589-2:2007 [5.2] states:

"The sample sheet enclosed with the sample or series of samples shall include at least the following information:

— identification and characteristics of the sample as indicated on the packing label;
— sampling technique and the associated equipment;
— date and time the sample was taken;
— name of the operator;
— any observations necessary to interpret the results; the topography of the sampling area, if uneven, is specified, particularly if the samples are taken from the following areas:
    1) in low-lying areas (trenches, plough furrows, depressions, etc.),
    2) on elevated areas (embankments, ridges, plateaus, etc.),
    3) in areas where the underlying rock is exposed,
    4) in marl pits, springs,
    5) on the edge of the area.

"When the study expresses the results of the analysis in terms of the surface activity..., the sheet shall also include

— the surface area sampled, S;
— the thickness of each layer sampled;
— the mass of the sorted sample, m_{SS};
— the mass of any subsample m'_{SS}.

"This sheet is completed, where necessary, with

— an evaluation of area homogeneity;
— a description of the use of the land;
— a description of samples;
— the weather conditions if samples are taken following an incident or accident.

"For samples from several depths, the sample sheet shall be completed with a description of the soil horizons, indicating the different layers and their physical characteristics (colour, texture, structure, percentage of coarse elements, etc.)

5.7.4. Sampling report

ISO 18400-102:2017 [5.9] states:

"The sampling report should contain, in addition to information on sampling location, personnel, observations and sample identification, a proper description of the sampling method and sampling devices used. If the actual sampling procedure differed from that originally planned, this also shall be reported, including the reasons for that change."

If preliminary investigations were carried out, a report should be prepared summarizing findings and stating the conclusions or any hypotheses drawn concerning the site conditions (i.e. geology, hydrology or possible contamination) relevant to the design of the sampling programme. The appropriateness of the adopted sampling strategy can thus be assessed at a later date [5.1]. ISO 18400-205:2018, Soil Quality: Sampling, Part 205: Guidance on the Procedure for Investigation of Natural, Near-natural and Cultivated Sites [5.11] states[3]:

[3] All citations from ISO 18400-205:2018 [5.11] are based on the wording used in the 2003 version.

"The sampling report prepared by the field staff should contain the following details:

- sample designation and number (identical to the marking on the sample container);
- date of sampling;
- information on the site (e.g. location, land use, textural class, weather conditions);
- description of soil profile in special cases;
- information on the procedure (field pattern, sampling equipment, depth of sampling, number of increments or composite samples etc.);
- information on storage and transport;
- information on the time and place of delivery to the laboratory;
- identification of sampler;
- counter-signature of customer or programme supervisor;
- confirmation of receipt by laboratory.

.....

"If soil samples are required from subsoil or underground for the investigation, more extensive procedures are necessary. Probing and drilling may be used and trial pits may be prepared."

In such a case, the sampling report may need additional information, such as on sampling techniques and procedures, packaging, storage and transport. ISO 18400-101:2017 [5.1] recommends the following:

"It should be clearly stated whether the sample was obtained from a trial pit, natural exposure, or by boring/drilling (given by inner diameter of tube, in millimetres).

"...and specifying in detail:

- the upper and lower limits of the horizon sampled, in metres;
- the upper and lower limits of the depth of sampling within a horizon;
- whether a single sample or a composite sample is obtained; and the number of increments and area for which the value to be measured should be representative;
- whether the sample is obtained in a horizontal or vertical direction in relation to the position of the horizon;

— the tools used to obtain the sample,... Also, the number of parallel samples constituting a composite sample should be stated, if relevant;
— whether the sample is related to volume or to mass."

.....

"In some cases a very detailed description of the site is required, which includes climate, weather conditions, surface relief, landscape, erosion features, exposure, slope, groundwater regime, improvement measures, vegetation, present and historical land use in the surroundings, sources of contamination, and others if specified by the customer."

REFERENCES TO CHAPTER 5

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Chapter 6

QUALITY ASSURANCE AND QUALITY CONTROL IN SAMPLING

6.1. PRINCIPLES

Effective decision making based on environmental monitoring data is fundamentally dependent upon the reliability of sample collection, the integrity of the samples, and the precision and accuracy with which they represent the true situation. Moreover, published data from environmental sampling campaigns can often attract the attention of the media. Subsequent analysis of poorly sampled data may lead to misinterpretation and the incorrect decisions being made. It is therefore essential that published results are of an acceptable quality and reliability. Failure to do so can ultimately result in the loss of credibility and even legal liability. The nature and potential impact of the site of interest and the desired level of confidence upon which decisions have to be made dictate the sampling objectives. The resources made available should therefore be commensurate with these factors (see Section 2.1, on the sampling strategy).

Quality assurance in sampling is obligatory for all sampling programmes and is an integral part of the overall planning process for the sampling campaign. Guidance on quality assurance can be found in many international and national regulations on the implementation of sampling programmes (further information on these can be found in Refs [6.1–6.6]).[1] However, the benchmark standard to which the quality control of sampling programmes should adhere is provided by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) in ISO/IEC 17025:2017, General Requirements for the Competence of Testing and Calibration Laboratories [6.7].

This chapter outlines the fundamental components required for a quality system in sampling for radiological monitoring. The system for quality assurance is a series of auditable and traceable procedures and actions that provide the assurance that the data meet the required standards of quality. It is intended to provide control over the collection of environmental samples, the interpretation of the samples and the validation of generated analytical data. Mitchell [6.8] reports:

> "*Quality assurance* (QA) is a system of activities designed to make sure that the data meet defined standards of quality. It pertains to the

[1] See also the MARSSIM Manual and resources available at www.epa.gov/radiation/multi-agency-radiation-survey-and-site-investigation-manual-marssim

overall management of the sampling program, and includes planning, documentation, training, consistency in collecting and handling samples, analyses, validation and reporting. An important part of QA is *quality control* (QC). Quality control refers to the technical activities used to reduce errors throughout the sampling program. These activities measure the performance of a process against defined standards to verify that the data meet the expected quality. Errors can occur in the field, laboratory or while handling the data. QC should include both internal and external measures. Internal QC is a set of measures undertaken by the project's own samplers and analysts. External QC involves people and laboratories outside of the project".

In view of the importance of the sampling campaign and subsequent analytical requirements, consideration needs to be given to whether a laboratory should be audited against and be compliant with the ISO/IEC 17025:2017 [6.7].

Radionuclides tend to be non-uniformly distributed in the environment, and the inter-sample variability is usually large because concentrations of radionuclides in the environmental compartments are spatially and temporally inhomogeneous due to the modes of deposition or subsequent processes of redistribution. Sampling procedures can be designed to either characterize or take account of the heterogeneity [6.4, 6.9]. Issues of heterogeneity can be compounded still further when accounting for the distribution of radioactive particles in the environment [6.9]; and in these scenarios, site characterization and sampling is greatly assisted by mobile gamma spectrometry techniques [6.10].

However, the analytical product of the monitoring programme and proper interpretation of the results cannot be made without full information on the design and characteristics of the sampling programme within the context of the history, condition and characteristics of the site from which the samples were collected. This information should be collected and included within a quality assurance programme, which should include the following:

(a) Information on the analytical and computational procedures and associated uncertainties and how these may be impacted by deviation from the agreed sampling protocols.
(b) Instruction on the nature, quantity, sampling plan and spatial distribution of samples to be collected. The sampling strategy should, where possible, be based on prior information and validated procedures and should also include an appropriate strategy for dealing with sites that cannot be sampled, for example due to insufficient material or the presence of an obstacle.
(c) Guidance on the sampling information that should be reported with each sample or set of samples and the methods used to undertake the sampling,

transport and storage. This should unequivocally document the origin of the samples and important physical and environmental characteristics that might impact their integrity.

(d) Clear instruction on the methods for sample identification, description, information and parameters that should be recorded, along with the method by which this information is recorded and reported to ensure that there is sufficient information for each sample description.

(e) Direction on sample storage, containerization and preservation requirements during transport back to the laboratory.

(f) Records of any deviation from the sampling protocol due to circumstances beyond the control of the sampling team (insufficient material available to be sampled) that might impact the true or determined analyte being reported.

(g) An audit trail which demonstrates that all steps and personnel involved in the methodology are audited at a suitable frequency.

For the quality assurance programme to be implemented effectively, a documented system of actions and protocols is required for traceable confirmation that the samples and subsequent data acquired meet the original objectives of the sampling strategy. These normally include the following basic elements:

— Justification of sampling strategy;
— Sampling equipment selection;
— Quality control of performance parameters;
— Documentation, including chain of custody;
— Training.

6.2. UNCERTAINITY DUE TO SAMPLING

The main purpose of environmental sampling and further measurements is to support decisions on environmental management or protection. The credibility or uncertainty of these decisions depends on the accuracy of the final results. These uncertainties can be separated into several parts (see Fig. 6.1) [6.11]:

(i) Uncertainty relating to sampling;
(ii) Uncertainty relating to sample integrity and preservation during transport;
(iii) Uncertainty relating to sample preparation;
(iv) Analytical uncertainty relating to the final measurement.

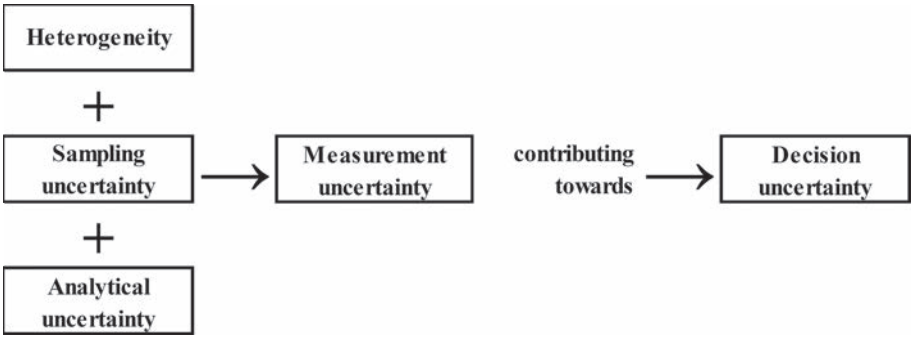

FIG. 6.1. Sources of the uncertainties affecting decision making based on environmental sampling.

When reporting results for any decision making process, it is necessary to account for the uncertainties arising from all data generation, including sampling, sample processing, and variability arising from samples and the heterogeneity in the sample matrix.

Sampling errors are largely a result of heterogeneity, either within the primary samples (fundamental error, grouping and segregation error, and increment delimitation and increment extraction error) or between the primary samples (long range and periodic heterogeneity error). The main types of sampling error and methods to reduce it are listed in Table 6.1.

Sampling errors can usually be minimized by using the appropriate sampling equipment and by carefully following the sampling and sample processing protocols. A short range spatial variation in the close vicinity of the sampling location should also be considered as a source of uncertainty.

The contaminants can be considered to be distributed in the topsoil, as is the case for many contamination scenarios. The deposition density, expressed as activity or mass per unit area, can be assessed by sampling the soil to a predefined depth and with a well defined sample area. The sampling tool and method should allow: samples of sufficient size to be collected; samples that do not exclude the largest soil particles (e.g. stones); and samples that have a shape that allows a consistent sample volume and cross-sectional area to be collected with increasing soil depth.

The sampling depth should be selected to make the sample extraction error as small as possible, taking into account the microtopography of the site (see Refs [6.13, 6.14] for details). For example, an error in sampling depth of 1 cm for a total sampling depth of 20 cm can result in a 5% error in the estimated soil contamination density. Sampling errors resulting from heterogeneities between the primary samples can be reduced by choosing an adequate sampling design

TABLE 6.1. CATEGORIES OF SAMPLING ERROR [6.12]

	Description/cause	Method of error reduction
Fundamental error	Loss of precision due to variation in particle size and composition	Increase the physical size of sample
Grouping and segregation error	Error due to distribution heterogeneities	Homogenization
Long range heterogeneity error of increments	Error due to the spatial or temporal trends	Using an appropriate sampling design or increasing the number of increments
Periodic heterogeneity error	Error due to the spatial or temporal trends	Using an appropriate sampling design or increasing the number of increments
Increment delimitation error	Error due to incorrect shape of the increment	Using appropriate sampling equipment
Increment extraction error	Error due to incorrect extraction of the intended increment	Using appropriate sampling equipment and following the sampling protocols
Preparation error	Error due to loss, contamination, or alteration of the sample during preparation and transport	Using appropriate sampling equipment and following the sampling protocols

Note: 'Increment' means the individual portion of soil or vegetation taken by a single application of a sampler.

and by increasing the number of samples taken from the sampling site. A good example of sampling uncertainties is provided by Van der Perk [6.15]:

> "In this study we examined the soil sampling uncertainty caused by the short-range spatial variability of elemental concentrations of As, Cr, and Zn in the topsoil of agricultural, semi-natural, and contaminated environments by means of two novel methods. For the agricultural site, where ploughing has reduced the variability in elemental concentrations in the topsoil, the relative standard sampling uncertainty is of similar magnitude to the analytical uncertainty, namely between 1% and 5.5%. In the semi-natural area, where the compositional variability is more or less natural, the

sampling uncertainties are 2–4 times larger than in the agricultural area. The contaminated site exhibited an extreme short-range spatial variability in elemental composition, which resulted in relative standard sampling uncertainties of 20–30%.

"Short-range spatial variability is inherent and unavoidable in soil physical and geochemical properties. The resulting soil sampling uncertainty can only be reduced by increasing the sample support, for example, by collecting multiple sample increments at a sampling location."

6.3. JUSTIFICATION OF SAMPLING STRATEGIES

The planning of sampling campaigns should start with the justification of the sampling strategy and selection of sampling sites, which should be fit for purpose and take into account the natural uncertainty of radionuclide distribution in the environment. The number of samples depends on the resources available, the nature of the investigation, and the accuracy and precision required. An assessment of the likely site characteristics should be undertaken based on the history of the site, experience from similar sites or preliminary site investigations. The sampling team should be cognizant of the project objectives and requirements, so that any impact of a necessary change in the sampling strategy can be assessed in subsequent sampling decision making. Any anticipated solutions should be included in the sampling strategy to main a systematic approach to sampling.

Sampling errors resulting from heterogeneities between the primary samples can be reduced by choosing an adequate sampling design (see Chapter 2). Further information can be found in Ref. [6.16], and Ref. [6.4] presents an overview of the different sampling designs in relation to the evaluation of the spatial means and standard errors (as a measure for the total uncertainty).

6.4. SAMPLING EQUIPMENT SELECTION AND HANDLING

The types of equipment available for sampling are detailed in Chapter 4. The equipment needs to be appropriate for the sampling objectives and matrix (e.g. vegetation, mineral or soil and stone content) and the volume or mass of sample to be collected, so these individual sample characteristics can be reproduced for all collected samples to maintain sampling precision with and between sites. Sampling equipment needs to be easy to use and maintain, so that with sufficient training samples are consistently collected and cross-contamination is minimized (e.g. cutting edges kept sharp and clean). Equipment should be

checked for any damage, which could cause misformed samples, smearing and cross-contamination. Sampling tools should be cleaned between sampling sites and pre-contaminated at each site (i.e. a dummy sample).

If sampling equipment is used to collect samples of a standard size or volume, this should be periodically checked, so that samples are within predefined tolerance levels of shape, size and volume. If site characteristics are known, it is important to progressively work from low areas of contamination to high areas.

6.5. CONTROL OF PERFORMANCE

Precision and accuracy are essential parameters for the quality of measurement and assessment. The control of both parameters should be part of the quality assurance foreseen in the sampling programme. The number and type of control measurements should conform to statistical requirements and tolerances prescribed in the sample design and the risk associated with management decisions to be made.

6.5.1. Replicate samples

The control of precision is done by replicate samples. The precision of the operator is determined by replicate measurements of the same site, with the same instrument using different operators; for instrument precision, the operator is the same but the instruments are different. Operator related measurement variability can be easily improved through training, although this can again vary depending on the nature and complexity of the sample and environmental conditions during the sampling campaign, and so it should be assessed and compared with both best and worst case scenarios.

6.5.2. Reference sites

In the laboratory, accuracy can be evaluated by testing certified reference materials of similar characteristics with the sample and which are typically homogenous, stable and certified for the activity concentration values for the radionuclides of interest. However, this is more challenging within sampling campaigns and necessitates the development and characterization of one or more reference sites [6.17]. For this to work, a reference site needs to be well characterized in terms of the spatial and temporal heterogeneity. Testing sampling tools and operator effectiveness requires suitable tolerances of performance against which to test. As described in Chapter 2, the anthropogenically derived radioactivity can typically reach a heterogeneity on the order of 30% or more.

This level of heterogeneity might be too large to test sampling tolerances. However, the heterogeneity of naturally occurring ^{40}K, uranium and thorium series is often demonstrably less than atmospherically derived anthropogenic radionuclides (e.g. see Ref. [6.17]) and may provide tighter tolerance levels (<5% or 10%), against which to test sampling tools and operator error.

A reference site may only need to be a stale area of 10 m × 10 m sampled with a 2 m grid to provide an estimate of the heterogeneity within the different soil and vegetation compartments. Unlike soil, the concentration of radionuclides within vegetation can vary depending on season, growth and environmental conditions (such as moisture stress). In all cases, the nature of the sample, including mass, volume, shape, completeness and integrity, is considered within the tolerance measures to assess the consistency of the tools and operators during training. The assessment of other factors, such as cross- or secondary contamination and smearing along the length of the cores, can then be assessed with radiometric techniques. A control point on the reference site can also be used to test the precision and accuracy of hand held GPS used to determine position of sample locations.

6.5.3. Deviations from the sampling standard

Actual field conditions can differ significantly from those present during routine training on the reference site. A tool used on one site may not be appropriate or sufficiently robust for another, which may affect the validity of the sampling methodology. When working in the field, procedures should take account of any deviations in sampling methods to ensure quality. This might simply require an adaptation of the sampling method or a different sampling tool. Fundamental to the success of the campaign is to ensure that any changes in sampling are documented and described fully, so that the sample characteristics (shape, volume, surface area and depth interval) can be easily reconstructed or interpreted. Any alternative method used should be pre-characterized so that the associated uncertainties are known.

6.5.4. Prevention of secondary contamination and losses

Cleaning procedures need to be in place to prevent contamination arising from equipment, tools and containers. Swabs taken after cleaning the sampling equipment can give indications on possible cross-contamination. Samples from the reference site will have known, low and well characterized contamination, which are collected and treated in the same way as real samples. Field blanks or control samples can be useful to demonstrate and document that no evaporation, absorption losses or gains, or cross-contamination in any form has taken place during sample transport.

6.6. DOCUMENTATION

6.6.1. Sampling strategy

It is the responsibility of the project management to ensure that all documentation (information, forms and protocols) is available to the sampling teams. This includes the basic considerations, health and safety risk assessments and site details used for the justification of the sampling programme as well as a proper description of the sampling sites. In addition, site access details and permissions need to be made available to the sampling teams. The sampling team is responsible for recording all information relating to the sampling campaign, including the location of sampling sites. A map can be very useful to visualize the site locations.

6.6.2. Sampling details

6.6.2.1. Details of sampling personnel

The personnel and the responsible person or team leader conducting the sampling is to be recorded. It is critical that those responsible for the sampling, containerization and recording is identified on the documentation. The personnel should be easily linked to the appropriate training records.

6.6.2.2. Spatial and temporal parameters

The time, date, frequency and location of the sampling point is required. The location for each sample site should be recorded, typically with a hand held GPS. The accuracy of the GPS should be known and tested against a well know control point. The GPS should be positioned directly over the mid-point of the sample location. The position above sea level can also be useful.

6.6.2.3. Physical characteristics of the sample

Physical characteristics of the sample include area, depth (including depth increment), height, length, volume, shape and size. Egli et al. [6.18] recommend:

> “The sample size refers to that portion that was removed from the environmental compartment under investigation.
>
> “Given the fact that hardly any environmental compartment is homogeneous, the sample size has to be chosen carefully depending

on whether the sampling should reflect or 'average-out' the lack of homogeneity. The larger the sample size, the lower is the sample-to-sample variability. Reporting the sample size is, therefore, indispensable.

"In case of on-line preconcentration during sampling (e.g., an adsorbance onto a media surface), the efficiency and capacity of the sampling device should be evaluated and reported."

6.6.2.4. Method of sampling

Sampling includes the tools, their condition (clean and worn but useable) and sampling strategy (grid, transect or random) [6.18]: "A description of the technique used [and tools employed] for sampling is mandatory, including a description of the equipment and the type of samples (replicate, grab, spatially or temporally composite samples)."

6.6.2.5. Meteorological conditions

The meteorological conditions include typical precipitation, wind direction and velocity, at the time of sampling and for the previous 24–48 hours.

6.6.2.6. Site characteristics

Site characteristics include the properties of the site and neighbouring land use, such as land cover, topography, proximity to woodland, "type and stage of tide in relation to yearly maximum and minimum (for coastal marine studies), or relevant anthropogenic activities adjacent to the sampling site (land use and agricultural practices, sewage systems, transport facilities...)" [6.18].

6.6.2.7. Sample integrity

Details include ample storage and preservation, including pretreatment. It is important that the nature of the sample material collected be documented, so that any change between collection and delivery to the laboratory can be identified and implications on sample integrity assessed. This is particularly important with perishable samples or where water content is significant in the final analysis and interpretation. Information on soil horizon, texture and species, for example, can be useful, especially when subsampled in the field.

6.6.2.8. Deviations from the sampling protocol

Any deviation from the sampling strategy according to predefined criteria needs to be recorded and to provide sufficient information to maintain the value and quality of the sample.

6.6.3. Traceability of samples and chain of custody

Sample traceability is an important quality assurance requirement and refers to the identification of the sample through the whole process of the characterization survey, starting with field sampling, transport, through to sample preparation, measurement and results reporting [6.2]. It creates the link between the final results and sampling location.

Good traceability includes the sample recording system, which gives each sample a unique identification, with no opportunity of replicating a sample code from other sites and thus leading to confusion. The sample labels should be resistant to environmental and laboratory influences (e.g. water and acid).

Fundamental to effective traceability is a chain of custody form. This form is retained with the sample or batch and clearly identifies who is responsible for the sample during sampling, containerization, transport, laboratory preparation, analysis, reporting and subsequent storage and disposal. At each stage the samples are handed over, each sample should be checked and signed for, so that there is a clear check on the sample and along with the transfer of responsibility.

6.7. TRAINING

All personnel involved in the sampling programme need to be aware of the quality assurance and control requirements, which may be specific to a sampling campaign, customer or user. Good documentation of the survey planning and related sampling and working procedures, as described in Section 6.6, along with previous experience and training are necessary to ensure best practice in sampling and subsequent data quality. The necessary training needs to be foreseen by the project leaders before the implementation of each sampling programme.

Only harmonized sampling and measurement approaches will guarantee comparable data, which can be used in an overall assessment and characterization of one or more contaminated sites. Regular checks or audits on sampling personnel should be undertaken, even with experienced staff, to ensure best practice and that the latest advances in sampling procedures are implemented. Auditing performance provides a traceable means of demonstrating competency and a mechanism through which training requirements can be identified.

The advantages of practical field training compared to theoretical training include the following:

(a) Personnel can take samples using the equipment and procedures available, benefit from immediate correction of any mistakes, and harmonize the methodology and procedures.
(b) Sampling equipment and any ancillary equipment can be tested and missing or damaged items identified and replaced in preparation for the sampling campaign.
(c) Documentation and recording requirements can be clarified and where necessary harmonized and improved.
(d) Measurement and sampling equipment used by different groups can be cross-checked, the measurement accuracy verified and where necessary improved by re-calibration, repair or replacement.
(e) Methodological problems can be discussed and critical points of the procedures emphasized.

Field exercises are organized by several organizations and can be used to improve knowledge and experience in sampling and in situ measurements and to define the uncertainty of the methods applied (see Refs [6.19–6.28]. Several publications discuss the uncertainty relating to sampling (see Section 6.2), but a clear separation of sampling method related uncertainty from other factors, such as survey area heterogeneity, measurement and other uncertainties, can be difficult and should be carefully planned to isolate each source of uncertainty where possible.

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Chapter 7

SAFETY ISSUES

This chapter provides relevant information on safety issues relating to the sampling of soil and other ground material. It is based on the International Organization for Standardization (ISO) standard ISO 18400-103:2017, Soil Quality: Sampling, Part 103: Safety[1], which states:

> "This part...provides guidance on the hazards that may exist during a site investigation and when collecting samples of soil and other ground material, including hazards that are intrinsic in the sampling operation in addition to the hazards that may arise from contamination and other physical hazards. Precautions are given so that the risks involved in any sampling or site investigation can be controlled and minimized.
>
> .....
>
> "This part...is designed specifically to deal with the problems of safety during sampling and site investigation, and is not intended to provide guidance for other situations such as construction."

This chapter provides additional guidance on safety for soil sampling of radioactively contaminated and mixed contaminated soils and other ground material (i.e. sediments and waste rock material), including sampling on legacy sites (contaminated areas), inside and outside controlled/monitored zones, in residential areas, agricultural areas, parks, greenfield and in forest areas. ISO 18400-103:2017 states:

> "The main objectives of this guidance on safety are
>
> a) to identify the hazards that may exist in carrying out site investigations and soil sampling programmes,
> b) to indicate management procedures to provide a framework for safe working and proper response in the case of accident,

[1] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Soil Quality: Sampling, Part 103: Safety, ISO 18400-103:2017, ISO, Geneva (2017). All citations are based on the wording used in the 2001 version.

c) to indicate what precautions can be taken in terms of personal protection and cleaning facilities to minimize any hazard, and
d) to indicate what working procedures can be adopted to minimize hazards from contaminants and physical hazards associated with the collection of samples and the use of machinery."

Soil sampling is carried out in compliance with the necessary approvals or permits in force and according to national regulations and laws. National legislation and systems for controlling the exposure of workers to substances hazardous to health should be complied with. When sampling radioactively contaminated soils or other material classified as radioactive, additional regulatory safety requirements may apply. ISO 18400-103:2017 states:

> "It is not possible to identify all the hazards which may be encountered during site work, nor to provide guidance on how the associated risks may be dealt with in all situations. Safety depends ultimately on the adoption of an attitude and approach to any particular situation which will ensure that the hazards are identified and properly evaluated, and appropriate precautions taken.
>
> .....
>
> "The guidance in this part...should be read in conjunction with relevant national and international legislation and regulations regarding health and safety at work.
>
> "In general, achievement of safe working conditions requires the employing organizations to adopt formal 'policies' and operating frameworks which will require and permit
>
> — identification of hazards and evaluation of risks,
> — avoidance of risks wherever possible,
> — failing this, control of the risks through adoption of appropriate operating procedures, and
> — failing this, or in addition, the protection of individuals against unavoidable risks.
>
> .....

"In order that appropriate risk reduction and management procedures can be identified, it is necessary, on a site-specific basis, to

— identify hazards,
— identify under what circumstance the hazards may present a risk,
— quantify the actual risks.

"In relation to contaminated sites, the importance of a desk study for identification of hazards from contamination and physical conditions must be emphasized."

7.1. IDENTIFICATION OF HAZARDS

The exposure of personnel to hazards includes the following:

(a) Fire and explosions;
(b) Solid and liquid chemicals;
(c) Gases;
(d) Bacteria and viruses;
(e) Radiation;
(f) Topography such as underground cavities, uneven ground surface, unstable voids at the surface (e.g. excavation pits);
(g) Overhead electrical cables;
(h) Underground services (pipes, pipelines, electrical and other cables);
(i) Machines;
(j) Buildings and other structures;
(k) Dangerous animals.

In addition to areas of investigation in general, ISO 18400-103:2017 also specifies hazards on agricultural sites, in contamination investigations, and in geological and geotechnical investigations. The presence of a radiation hazard due to previous operations on a site should be researched and evaluated in advance of any field work relating to soil and vegetation sampling for radiation monitoring. With any site investigation, precautions and personnel monitoring should be considered to ensure that harmful doses are not received. With regard to particular hazards on agricultural sites, ISO 18400-103:2017 states:

"Radiation hazards normally only exist from the existence of fall-out, due to either a public incident or the proximity of a nuclear installation. For

such occasions on-site, it will be self-evident that a hazard may exist so that precautions can be taken."

In addition, a radiation hazard can come from discharges, spillage, outflow, runoff or flooding of water contaminated with radioactive substances.

With regard to particular hazards in contamination investigations, and in geological and geotechnical investigations, ISO 18400-103:2017 states:

> "In addition to possible fall-out hazard..., it is also possible that the former industrial operations used radioactive material. Such usage or the possibility of such usage should become apparent from the desk study. Use of radioactive material is normally tightly controlled and monitored by the appropriate national authority, which can advise on the potential risks at a particular site.
>
> .....
>
> "Apart from the hazards described [above], there may be natural radioactivity as gas (radon) or possibly from rocks (granite) which might create a hazard if repeated exposure is experienced by a particular sampler. Such exposure is only likely to be of serious concern if it occurs frequently and in confined spaces such as underground caves or mines."

In particular, exposure to radon gas can come from different sources in the area surrounding the site — even from one or more sources that seem to be out of the scope of the soil sampling programme. The radon exhalation at a given location and time can also be influenced by human activity in the area.

7.2. SAFETY PRECAUTIONS

ISO 18400-103:2017 states:

> "**6.1 Safety policy**
>
> "Any organization involved in site investigations and sampling should have a safety policy which sets out the requirements for safe working. ...The policy should:
>
> — insist on adherence to relevant legislation and regulations,
> — emphasise the need for alertness and vigilance on the part of site personnel to protect themselves from hazards during investigation and sampling,

— emphasise the requirement to follow standard operating procedures where these exist,
— describe the responsibilities of each member of the investigation team, including the responsibilities to any sub-contracted personnel and to the general public,
— include a mandatory ban on smoking, eating or drinking while on site carrying out a sampling exercise or other site investigation.

"The policy should be supported by standard procedures setting out the requirements for safe working in general, and in specific locations such as confined spaces. These standard procedures should include the provision and use of protective clothing and equipment, and the minimum number of personnel that should be involved in site work. The standard procedures should also specify the requirements for contacting local emergency services, methods of communication and methods of washing and decontamination.

"6.2 Planning and managing for safety

"To assure the safety of personnel in site investigations or sampling exercises, it is necessary to plan and manage for safety. This requires a combination of measures which may need to include

— assessment of the hazards arising from the site,
— avoidance of hazards where possible,
— selection of sampling methods with safety in mind,
— provision and use of personal protection equipment,
— provision of equipment for the detection of hazardous environments,
— provision of appropriate personnel site facilities,
— provision of decontamination facilities for personnel and equipment,
— appointment of an individual to take responsibility for implementation of safety plan and measures,
— clear assignment of responsibilities,
— documentation of safe working procedures,
— 'permit to work' system,
— provision of information to all concerned,
— training,
— provision of first aid facilities,
— planning and use of emergency procedures,
— installation of system of record-keeping of 'incidents' and possible exposures,

— health surveillance,
— compliance with company safety policy (see 6.1),
— compliance with national laws and regulations concerning the health and safety of the personnel and the general public.[2]

.....

"Prior to undertaking any form of investigation on a site, it is essential that an assessment of hazards be carried out. This is particularly important on former industrial sites and waste sites. If site reconnaissance forms part of the preliminary investigation, the hazard assessment should be based on the results of the desk study. It may be possible to refine the assessment once the preliminary investigation is completed, and it should be kept under review as the investigation proceeds. ...

"National legislation and systems for controlling the exposure of workers to substances hazardous to health should be complied with. Precise requirements may differ, but often include a framework requiring

— avoidance of exposure when this is reasonably practicable,
— if this is not possible, use of control measures to prevent exposure or limit exposure to 'permitted levels'..., and
— if this is not possible, the use of personal protective equipment.

.....

"**6.3.5 Radiation hazards**

"Where radiation hazard is possible, dose-monitoring badges should be worn as minimum, but it is preferable to take specific advice from a national radiation authority. If personnel are routinely involved in work below ground level in an area of known significant radon concentrations, specialist [advice] should also be obtained."

[2] Some measures for protection, monitoring and control are given in table 1 of ISO 18400-103:2017.

7.3. SAFETY PROCEDURES

ISO 18400-103:2017 states:

"**6.4.1 General**

"Each site should be studied prior to a visit and safety procedures reviewed in the light of the particular features involved. ... In the case of contaminated site investigations, ... there are likely to be particular precautions or more stringent application of precautions due to the features of a particular site.

"In most cases, a minimum of two people should be on a site, with means of external communication. If only one person is on site, e.g. for agricultural purposes, some system of reporting should be established to ensure the safety and well-being of the site worker.

"Upon completion of the sampling, any protective clothing should be carefully removed and wrapped up to prevent spread of contamination. ... Clothing and other protective equipment should not be taken to any residence for washing or cleaning under any circumstances.

"Hands and face should be washed before leaving the site.

"Sample equipment should be cleansed and any contaminants contained to prevent their spread. The samples should be prepared for despatch with suitable labels, ensuring that there is no contaminated material on the outside of the container. There should be a special note on the label to advise the laboratory, or other persons receiving the sample, if there is any known or suspected contamination which presents a particular hazard. The method of despatch should ensure that samples arrive at their destination without spillage of distribution of contamination.

"National regulations and legislation regarding packaging and transport of hazardous materials and wastes should be observed where appropriate."

Care should be exercised at the sampling site if there are buildings or constructions above ground or below ground that could pose a risk to the workers. With regard to agricultural sites, ISO 18400-103:2017 states:

"Particular care should be exercised if working near bodies of water such as streams, pools, rivers and lakes, and also in the vicinity of slurry [i.e. soft

tailings].... Particular care should be exercised if...there is some feature of the land which may present a hazard."

Regulations for the transport of radioactive material will depend on the radiological properties of a single sample or of a number of samples (characterized by the overall mass or volume). Specific safety procedures will apply to soil and vegetation sampling from very contaminated sites or controlled areas such as radiation protection zones. ISO 18400-103:2017 states:

"On very seriously contaminated sites it may be appropriate to have a designated clean area, with access to and from the site by way of a decontamination unit.

"It is essential to avoid damage to any mains services, if necessary by using hand excavation. ...

"Before commencement of the investigation, it should be known whether below-ground voids are to be entered and provision made for shoring the walls of any excavation. Other precautions should also be taken, such as the supply of safety harnesses and breathing apparatus."

If the sampling area has been affected by war activities (e.g. bombings, mines and munitions), additional safety measures may be necessary (i.e. applying geophysical survey methods and geophysical borehole measurements) to provide a release for sampling points before the sampling can be carried out. Additional, specific safety procedures also apply if samples are taken underground in caves, mines or other underground voids.

7.4. SAFETY EQUIPMENT

ISO 18400-103:2017 provides information on safety equipment which can be used in making soil and vegetation sampling a safe operation:

"The list includes:

- chemical-resistant safety boots (not laced) with steel toe and sole protection;
- gloves (heavy-duty chemical-resistant);
- overalls (waterproof if necessary);
- eye protection such as glasses, goggles or face shield;

- ear protectors;
- protective helmet;
- high-visibility vest or jacket;
- safety harness;
- breathing apparatus and operator;
- washing and toilet facilities (these can vary from provision of water, soap and a towel...to a fully plumbed-in decontamination unit...);
- gas monitors;
- radiation monitors;
- services monitors/detectors;
- site telephone;
- eating and resting area;
- vehicle-washing facility to prevent transport of contamination from the site.

"The use of safety or protective equipment should not result in contamination of the samples collected, and the equipment should be selected accordingly."

7.5. REMARKS ON GENERAL ENVIRONMENTAL SAFETY

ISO 18400-103:2017 states:

"In any sampling investigation there will be some disturbance of the ground. ...

"Examination of sites suspected of contamination does however pose some risk to the general environment.

.....

"Investigation of such sites results in contaminated material being brought to the site surface and disturbance of below-ground strata, in addition to the possible perforation or destruction of the surface cover."

The same applies if sampling leads to perforation of a baseliner or sealing layer below the sampled strata or if the perforation of investigated strata themselves could result in an adverse environmental impact (i.e. by additional seepage into underlying or surrounding underground layers). The field investigation works and in particular the sampling itself leads to open voids in

the sampled strata. If not properly backfilled, such voids can facilitate the ingress of water and gas into the sampled strata. In addition, they may also facilitate gas emanation (i.e. radon) from the sampled strata to human beings and to the environment. ISO 18400-103:2017 states:

> "Material exposed on the surface can present a hazard to the environment. ...
>
> .....
>
> "Regard should be paid to local regulations which may require off-site disposal of suspect material and backfilling with clean material.
>
> .....
>
> "When carrying out an investigation on highly contaminated sites, consideration should be given to using only borehole or probing techniques and not excavation, as a means of minimizing disturbance and reducing problems of increased distribution of contamination."

Where boreholes or excavation penetrate impermeable soil layers, like clay strata, such voids should be plugged or backfilled with impermeable material, respectively. If the site is obviously contaminated prior to the investigation, and presents a general environmental (or radiological) problem due to exposure to the relevant recipients, additional measures may be required to prevent the spread of contamination.

Chapter 8

CASE STUDIES

8.1. SAMPLING PROGRAMMES IN THE AREAS AFFECTED BY THE ACCIDENT AT THE CHERNOBYL NUCLEAR POWER PLANT

The accident at the Chernobyl nuclear power plant was the biggest radiation catastrophe in history, affecting to the greatest extent the rural population and agricultural production in the three most contaminated countries — Belarus, the Russian Federation and Ukraine. Large areas of Europe were contaminated: more than 200 000 km^2 had contamination densities above 37 kBq/m^2 [8.1]. Various criteria and approaches for the evacuation and resettlement of the population, for restrictions of food production and for remediation of the contaminated areas were applied. Soil and vegetation sampling programmes conducted in areas affected varied with the time since the accident. In the initial period following the accident, the main purpose of sampling was to assess the overall consequences and to determine the actions required to protect the population and how best to support their implementation. It was important to define quickly the soil contamination in the areas officially recognized as contaminated. The official demarcation of a contaminated area was defined at 37 kBq/m^2 by ^{137}Cs [8.2].

The implementation of the sampling programmes was supported by airborne and external dose surveys made in the vicinity of the Chernobyl nuclear power plant. Major first efforts were directed towards mapping ^{137}Cs contamination to identify areas where direct protection of the population was required according to radiation protection standards.

At the end of May 1986, the evacuation zone (effective dose > 100 mSv) was classified with a dose rate above 50 μSv/h (for external exposure >50 mSv/a) and the village areas where the average density of soil contamination with long lived, biologically significant radionuclides exceeding 555 kBq/m^2 for ^{137}Cs, 111 kBq/m^2 for ^{90}Sr and 3.7 kBq/m^2 for $^{239,240}Pu$ (for internal exposure >50 mSv/a). Officially, such zoning was carried out in July 1986 by the Union of Soviet Socialist Republics (USSR) State Committee for Hydrometeorology after the approval of maps of radioactive contamination [8.2].

Beginning June 1986, the density of radioactive deposition in the contaminated regions were mapped, and two months later nearly all farmland had been surveyed. In the two to three years following the accident, improved sampling programmes were developed separately for farmlands, forested areas and settlements. These sampling programmes were developed mainly to identify mid and long term countermeasures and remediation programmes to mitigate

the consequences of the accident at the Chernobyl nuclear power plant [8.3]. The specific feature of these programmes was combining external dose rate measurements with soil and vegetation sampling. A summary of the sampling programmes implemented in different periods following the accident is given in the Annex, which includes the sampling programme objectives, the types of sampling and equipment, and references to additional information about the programmes.

8.1.1. Mapping contaminated areas

Sampling programmes to identify contamination levels around the Chernobyl nuclear power plant began in the very first days after the accident. In the 10 km zone, they were performed by the USSR Ministry of Defence, and outside the 10 km zone by the USSR State Committee for Hydrometeorology. The first complete map of the nearest trace (to 100 km from the plant) was plotted within five days after the accident [8.2]. The State Committee for Hydrometeorology together with the Ministries of Geology and of Defence also investigated terrestrial contamination density using airborne gamma spectrometry [8.4]. Extensive soil sampling in contaminated areas was carried out by various organizations, which analysed the samples using gamma spectrometry and radiochemical methods. They used a variety of methods to sample the soil and vegetation: immediately after the accident, there was no approved common method. Later recommendations were the use of 14 cm diameter rings for soil sampling on uncultivated land to a depth of 5 cm.

A 10 km grid was first used in 1986 to determine ^{134,137}Cs contamination density. The grid was then refined in 1991 to one measurement point in each square kilometre. The numbers of sampling points for ^{90}Sr and plutonium radioisotopes were 10 and 100 times fewer respectively than those for ^{137}Cs [8.2]. The first maps of ^{137}Cs and $^{238–240}$Pu contamination density for the accident zone were created in 1986 based on soil sampling and measurement.

For the long term monitoring and mapping (including ^{134,137}Cs, ^{144}Ce, $^{238–240}$Pu, ^{106}Ru, ^{90}Sr and ^{95}Zr+^{95}Nd) of the 60 km zone in 1987, a radial network was created of control points (540 points) in every 10° (from 10° to 360° clockwise) at distances 5, 6, 7, 8.3, 10, 12, 14, 17, 20, 25, 30, 37, 45, 52 and 60 km [8.5, 8.6]. Soil samples were taken every year from 1987 to 1992 at these control points (see Fig. 8.1).

Sharp edge rings were constructed from segments of a steel pipe sharpened along one edge; 14 cm in diameter and 5 cm deep, they were used to sample soil and dense sod (see Fig. 8.2). The ring was hammered into the soil and then retracted with the soil plug inside. The soil sample and ring were packaged together to maintain integrity without mixing. Each sample was measured in

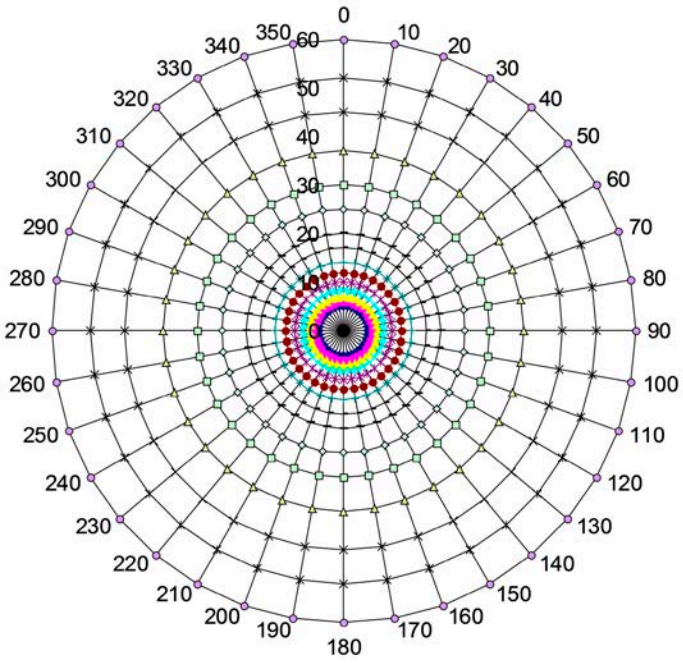


FIG. 8.1. Radial network (grid) of control points in the 60 km zone, 1987–1992.

FIG. 8.2. Sampling with a 14 cm ring. (Courtesy of Ukrainian Institute of Agricultural Radiology.)

a gamma spectrometer twice (turning the ring after the first measurement) to obtain an average. At each sampling unit, soil samples were collected from five points (based on the envelope sampling approach with 5–10 m between sampling points, see Fig. 8.3), and the activity was measured by different organizations.

At the end of 1988, horizontal plates covered with gauze (0.5 m × 0.6 m) were also added, which were installed at control sites to determine the extent of resuspension of radioactive material. To measure the vertical distribution of the radionuclides in soil, special cylindrical samplers (55 mm in diameter and 200 mm long) of two separable parts placed in the tube were used (see Fig. 8.4). After sampling, the soil core was sectioned with a knife (starting with the least contaminated bottom) in 1 cm to 5 cm intervals, depending on the task. Based on the dose rate and soil sampling measurement data, more detailed maps of the contamination density of ^{137}Cs, $^{238–240}$Pu and ^{90}Sr were created in 1990 (see Fig. 8.5).

The contamination density of gamma emitting radionuclides (^{144}Ce, ^{95}Nb and ^{95}Zr) can be promptly measured by remote aerial survey methods (e.g. airborne gamma ray spectrometry), without the need to collect soil samples to be analysed later in a laboratory [8.9]. However, these techniques were not conducted promptly after the accident and before the radioactive decay of gamma emitting radionuclides with medium half lives [8.10]. More detailed contamination density maps of the 30 km Exclusion Zone with no gamma emitting radionuclides (^{90}Sr, ^{238}Pu and $^{239+240}$Pu) were created only in 1997–2000 after the completion of the soil sampling campaigns (see Fig. 8.6).

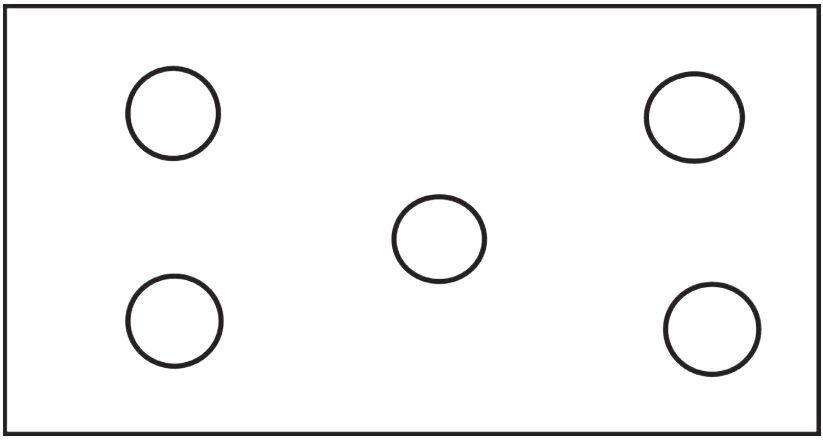


FIG. 8.3. Scheme of sampling points based on the envelope sampling design.

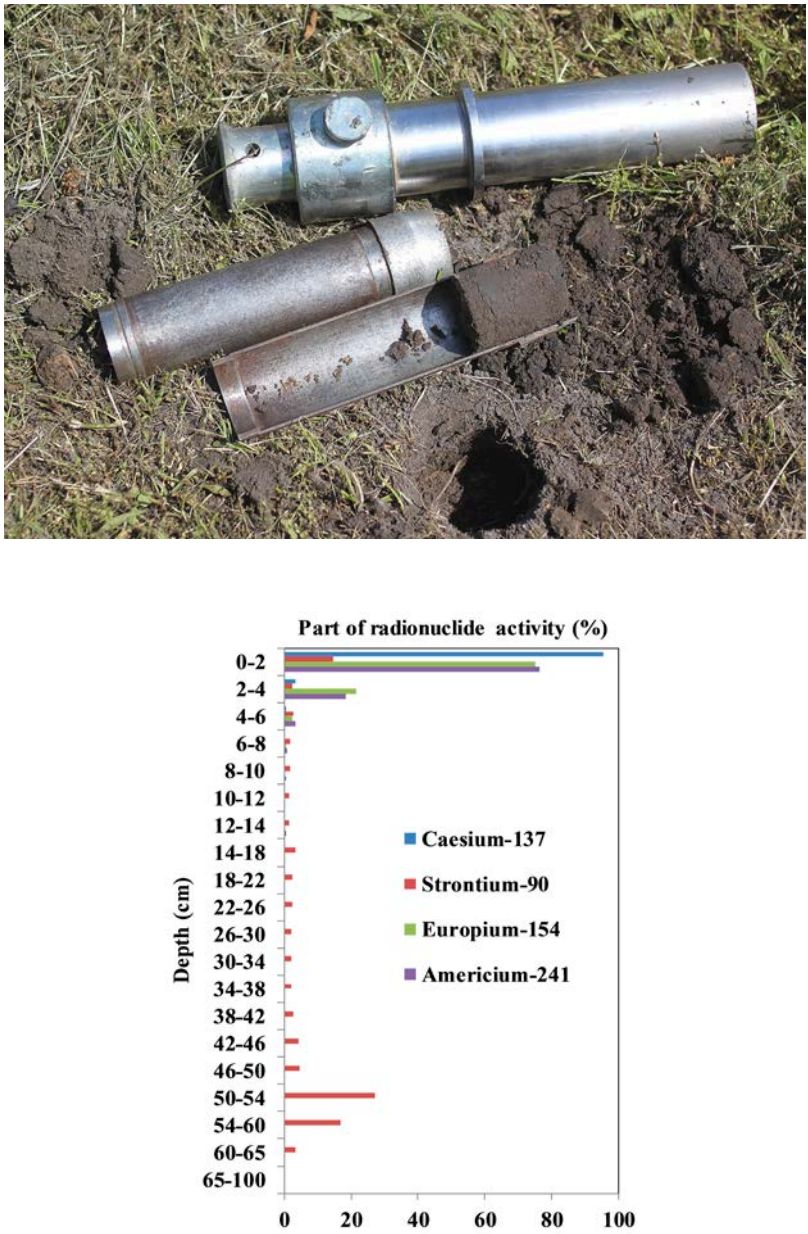


FIG. 8.4. Sampler for the measurements of the radionuclides vertical distribution in soil (top) and the depth distributions of radionuclides in low humified sandy soil (bottom) [8.7].

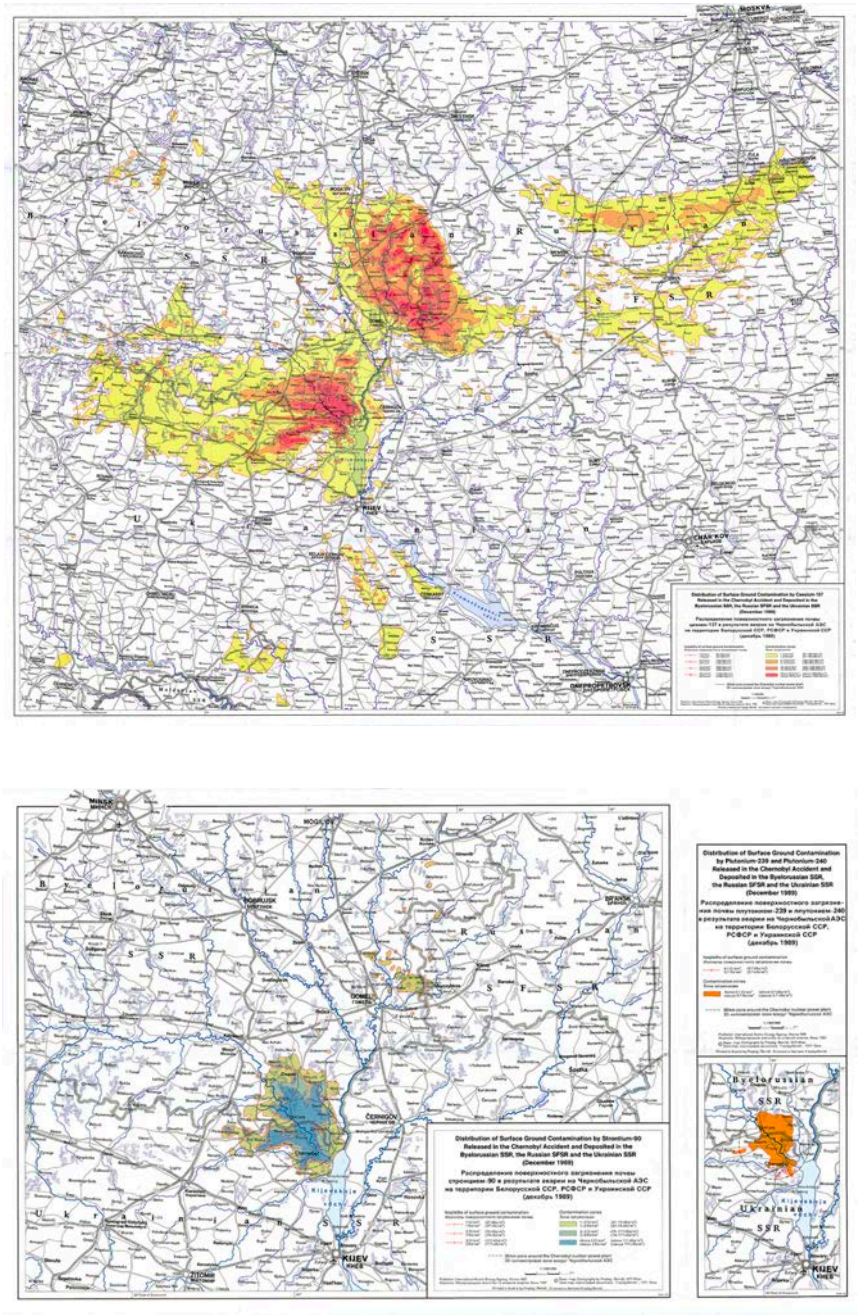


FIG. 8.5. Maps of contamination density with ^{137}Cs (top) and ^{90}Sr, $^{238–240}Pu$ (bottom) in 1990 [8.8].

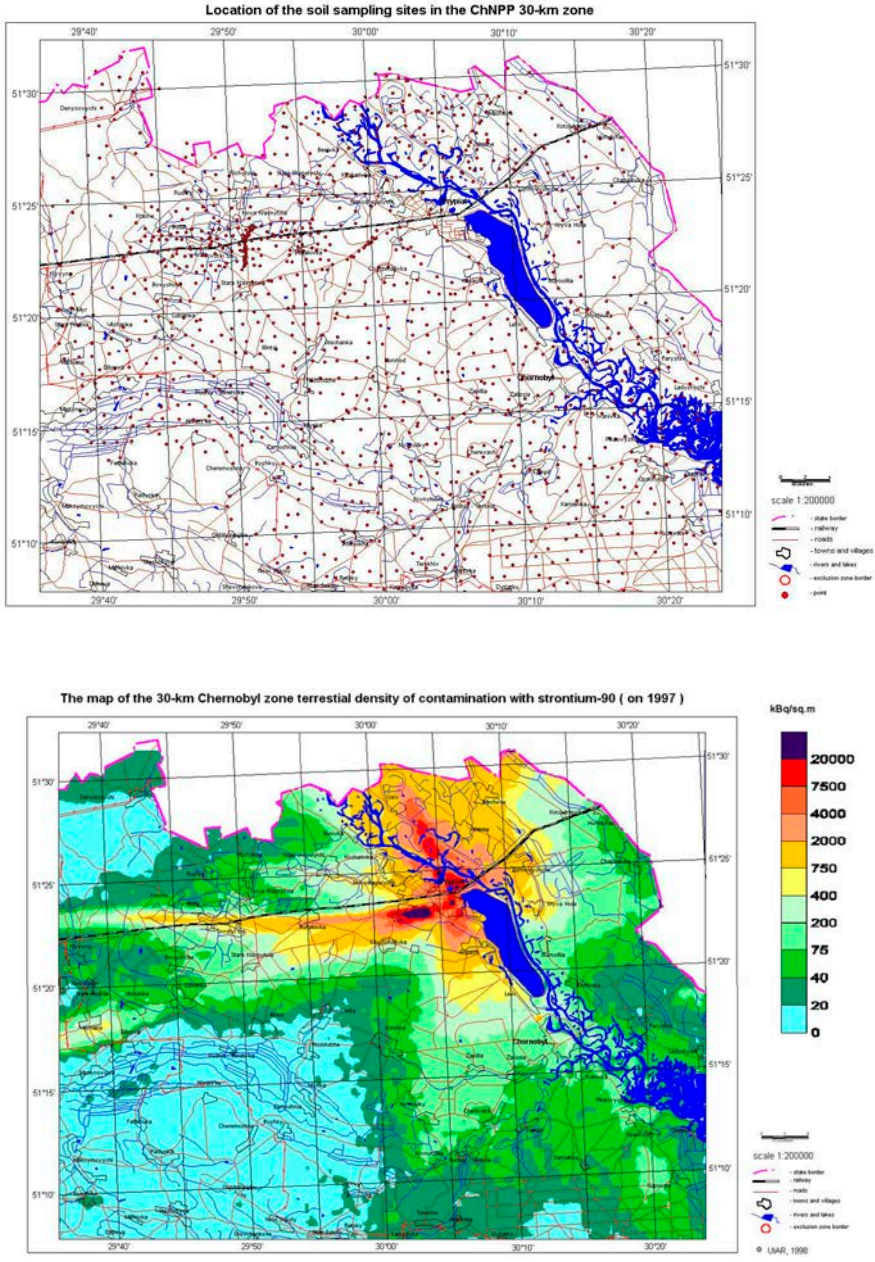


FIG. 8.6. Regular network (grid) of sampling units in 30 km zone in 1997 (top) and map of ^{90}Sr (bottom) contamination density [8.11].

Kashparov et al. [8.12] report on samples collected in Ukraine at regular grid locations in about 1300 sampling units at distances up to 36 km from the Chernobyl nuclear power plant (see Fig. 8.7):

> "In general, the distance between sampling units was about 1.2 km. The distance was lower (100–500 m) at the narrow western trace of the radioactive fallout, which is characterized by the very high gradients of contamination. ... Taking into account that the sampling area is rather large (about 2000 km^2) and that some sites are now hardly within reach, the sampling was done using both helicopters and cars.
>
> "Each soil sample consisted of five sub-samples of cores of 37 mm diameter, taken in the corners and in the centre of 2–5 m^2 to 30 cm depth. Thus, the total mass of each sample was about 3 kg."

FIG. 8.7. Sampler with a diameter of 37 mm (0.001 m^2).

Based on all dose rate and soil sampling data after the accident at the Chernobyl nuclear power plant, more detailed maps of the contamination density were created to better present the area of radioactive contamination. Based on this sampling programme, the area with ^{137}Cs contamination density greater than 40 kBq/m^2 (in 1986) was substantially re-evaluated. Areas thus identified amounted to 65 100 km^2 instead of the 59 800 km^2 based on a previous survey in what is now the Russian Federation and from 42 800 km^2 instead of 38 200 km^2 in Ukraine [8.12, 8.13]. Accordingly, additional efforts were applied for radiation protection of the population and for remediation.

8.1.2. Contaminated settlements

The objective of the soil and vegetation sampling programmes was to identify the affected settlements requiring different radiation protection measures for the population. Such a classification was based on the contamination density of the main dose forming radionuclides (see Table 8.1) [8.7].

8.1.2.1. Selection of sampling points

Soil sampling selection in the contaminated settlements was supported by the measurements of external dose rates, which were conducted at heights of 1 m and 3–4 cm above the ground. Five main sampling units were selected to cover the whole area of the settlement. The points were chosen so that one sampling point was closer to the centre of the location and the other four on its periphery. If areas were found where the external dose rates were twice the average for the settlement, then additional soil samples were collected. The positions for soil sampling were selected in areas where the soil surface was undisturbed after the

TABLE 8.1. CLASSIFICATION OF CONTAMINATED AREAS

Zone	Contamination density (kBq/m^2)		
	^{137}Cs	$^{238–240}Pu$	^{90}Sr
Zone of guaranteed resettlement and evacuation	555–1485	>3.7	>111
Zone of guaranteed voluntary resettlement	185–555	0.37–3.7	5.5–111
Zone of enhanced radioecological monitoring	37–185	0.185–0.37	0.74–5.5

nuclear accident and where soil losses or alluvium deposition at the soil surface had not occurred. Preference was given to grass covered areas at least 5 m long; sandy areas without any grass cover were avoided. The sampling units were normally selected on flat, uniform and open areas. The distance from the nearest buildings and trees was at least twice their height, and at least 20 m from dirt roads.

External exposure dose rate was measured with a certified dosimeter in the junctions of the grid at a height of 1 m. In each yard, garden, kitchen garden and inside the house, the dose rate was measured to identify and localize any anomalous hot spots of contamination. In small villages, the dose rates were measured in at least five points of every yard, starting from its entrance; in medium sized villages in each third yard; and in the large villages in every fifth yard. The sampling points were selected on account of the data acquired when estimating dose rates for the whole settlement as well as the data survey of each yard. In settlements with up to 350 yards, ten samples for gamma spectrometry were taken; and for every 35 yards above this number, one additional sample was taken. Five samples were taken for the radiochemical analysis of ^{90}Sr for each 350 yards. In the case of anomalies in the dose rate measurements, the soil was sampled, too. Before measurements, samples were mixed.

A detailed survey of settlement contamination began in 1989 because during the repeated studies, separate points or spots, not large in size and with higher contamination densities, were found in a number of settlements. This was first connected with the degree of survey detail, where the distribution of radioactive substances was extremely heterogeneous. The heterogeneity in many settlements was also determined from: the redistribution of radioactive material after its migration from more contaminated zones; the formation of ash concentration; waste from animal farms; and the concentration of radionuclides under roof spillways. For example, in Korosten, Ukraine, with an average contamination density of 250 kBq/m^2, around 1000 measurements were made with a uniform grid and several hundreds of local spots were found where contamination densities exceeded the average value by a factor of 20–30 (see Figs 8.8 and 8.9). The total area of these local spots was 16 000 m^2, and it occupied less than 0.1% of the whole town (35 km^2). In addition, some settlements are located in areas with great heterogeneity of radioactive deposition (due to high gradients of fallout density in the transection of radioactive trace and spots), which required a more detailed survey [8.6].

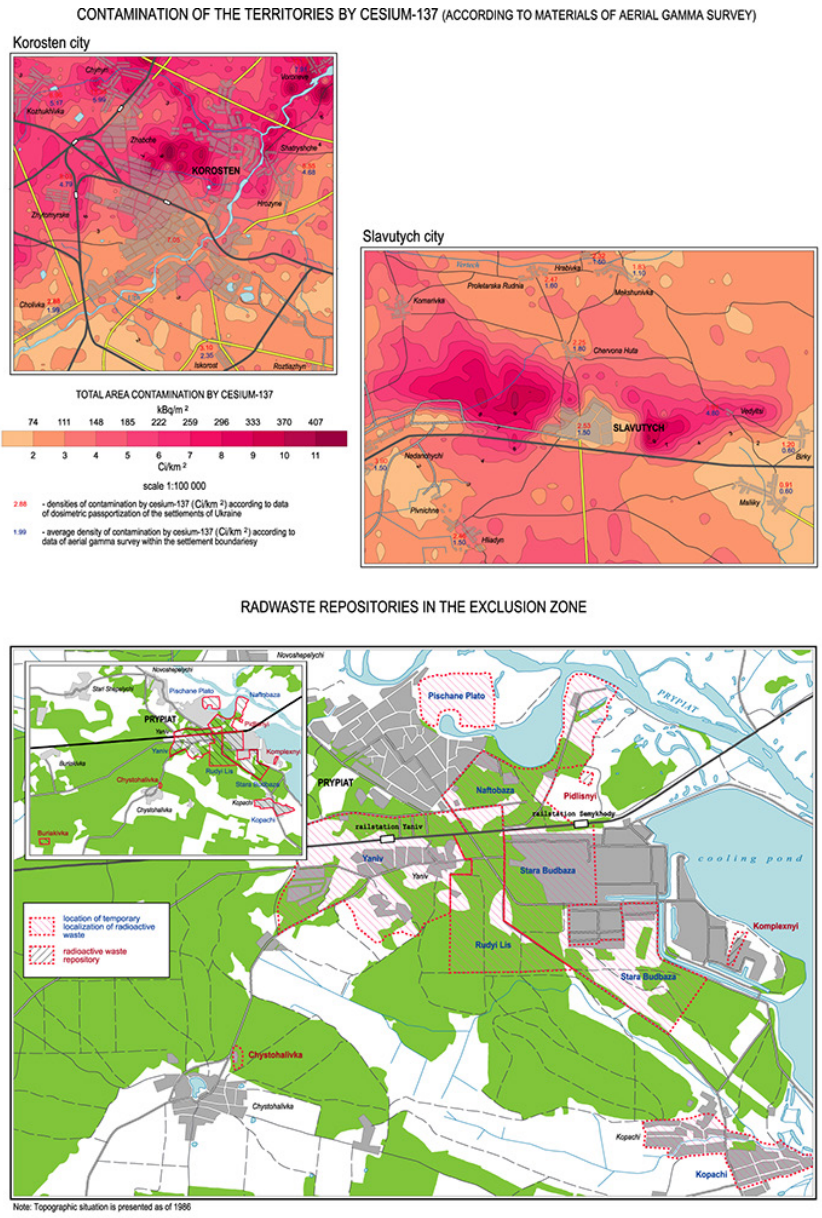
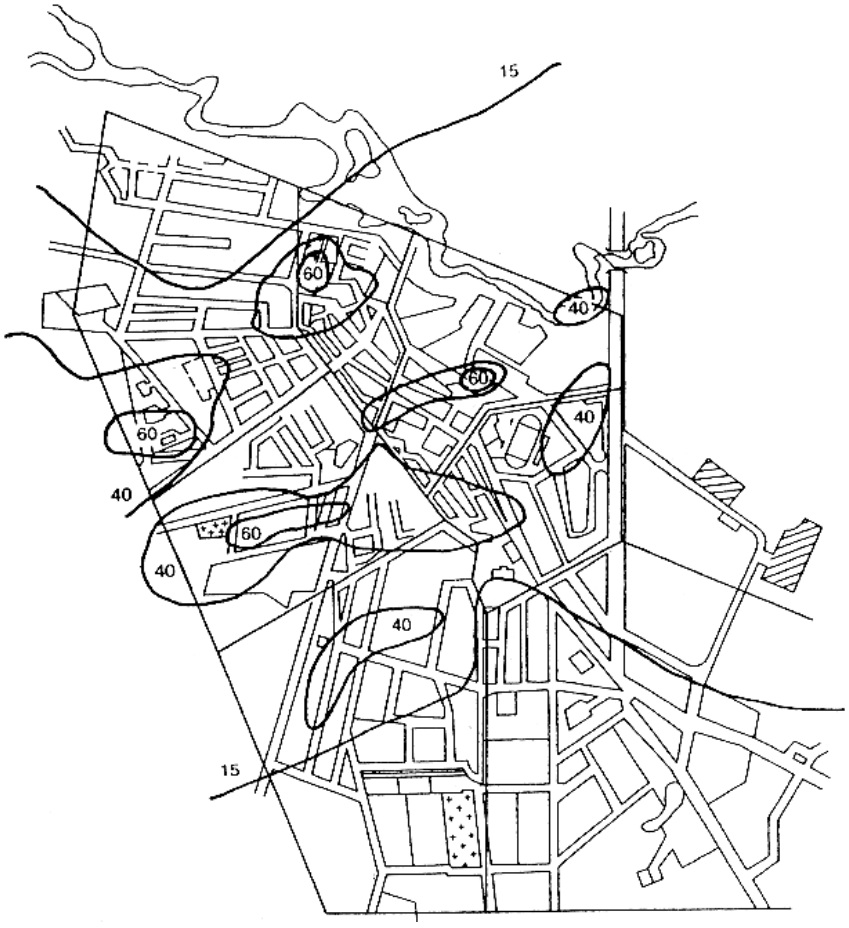


FIG. 8.8. Density of ^{137}Cs contamination Korosten and Slavutych [8.14].



Source: Official Soviet map [8.6].
Note: 15, 40 and 60 Ci/km^2 = 555, 1480, and 2220 kBq/m^2.

FIG. 8.9. Total ^{134,137}Cs deposition in Polesskoe (Ci/km^2).

8.1.3. Farmland 1986–1990

8.1.3.1. Arable soils

One of the main purposes of the soil and vegetation sampling was a classification of the agricultural land by the soil contamination density to support the implementation of remediation programmes for the contaminated areas. A criterion for termination and restrictions of the economic use of agricultural land was the average ^{134,137}Cs contamination density.

The first survey of farmland was performed in summer to autumn 1986. From 1987, soil and vegetation samples were collected before spring fieldwork and immediately before harvesting. The sampling was carried out so that the maximum area with different contamination densities, main types of land usage, soil types, subtypes and relief elements were obtained. Sampling units represented individual fields occupied by one crop.

For arable soils, samplers with a known sampling area were used, typically 4 cm in diameter. Samples of arable land cultivated after the accident were carried out at a depth of arable layer (as a rule, not less than 20 cm) and of land not ploughed since the accident at a depth of 10 cm. The recommended sampling design for the selection of composite samples used for mapping is given in Table 8.2 [8.15]. Table 8.2 also lists the requirements for selecting sampling units to obtain one composite sample per unit. The requirements are based only on contamination density. The selection of sampling units and the actual numbers of composite samples used for a radiological survey of arable soils were set depending on the diversity of soil properties and area occupied by individual crops, among other things.

TABLE 8.2. REQUIREMENTS FOR THE SELECTION OF COMPOSITE SAMPLES

Contamination density (kBq/m^2)	Min. individual samples used for one composite sample
<37	5 samples on the district (area)
37–260	1 sample on the farm
260–555	1 sample from 400 ha
555–1480	1 sample from 100 ha
>1480	1 sample from 40–50 ha

Each composite sample comprised ten or more individual samples uniformly spaced over the entire area of the sampling unit. Samples were taken to a depth of the typically ploughed layer (20 cm). The individual samples were homogenized to prepare a composite sample of at least 2 kg.

8.1.3.2. Non-arable soils

For non-arable soils in the first and second years after the accident, 100 m × 100 m sampling units were selected to account for typical landscapes, soils and contamination levels. Before soil and vegetation sampling, the external dose rate survey with the measurement points selected at the perimeter of the sampling unit and two diagonals were performed to assess inhomogeneity of soil contamination within the unit. The samples were taken based on the envelope design at five sampling points (see Fig. 8.3). The soil samples were taken with the standard metallic ring (14 cm in diameter and 5 cm long).

In the third year, only grass covered areas were selected. In 1987 and 1988, the standard rings used were placed above each other in the special sampler. The sampler had a sharp edge, high enough for the ring set to fit within and an inside diameter no less than 3 mm greater than the outside diameter of the ring. The sample collecting device (the ring or the conductor with the rings) was hammered into the soil up to the top edge, allowing the grass and soil to pass through the inside. The ring with soil was skimmed underneath with a spade, carefully cut around the lower edge of the device (it was desirable to cover both sides with plates) and put into a plastic bag or wrapped in polyethylene film. Above the bag, the sample was tightly wrapped in paper and roped with string. When sampling with the conductor, the rings with soil were removed and packed in the standard way.

Vegetation samples were collected at the same time and the usual area was 1 m^2. The cutting height was 3 cm higher than the soil surface. Where vegetation yield was low, the sampling area was increased to obtain a sample of at least 1 kg. Composite samples were wrapped in craft (hard) paper and labelled. The number of vegetation samples was the same as for soil samples. Information on vegetation species and the phase of vegetation were provided on the sheet assigned to each sample.

8.1.4. Agricultural areas mid and long term after the accident

8.1.4.1. Selection of sampling units

Accuracy of the data produced by the sampling programmes was extremely important to determine the remediation strategies. A few years after the accident, the sampling programme for farmland was improved based on the prior sampling

experience, which allowed the sampling programmes to be optimized. The data of the first surveys were widely used to determine sampling plans for further surveys, and sometimes they were used to assess contamination levels of areas that had not been surveyed, for whatever reason. For example, data on ratios between ^{137}Cs contamination densities and dose rates on both cultivated and non-cultivated land, obtained after the accident, were widely used to assess agricultural land that had not been surveyed to identify hot spots and to determine remedial actions.

Experience showed that detailed maps of contamination for each field were required rather than averaged data derived from large scale maps. Other important data collected included the accumulation of radionuclides by agricultural plants and soil properties — parameters specific to each field. Individual field surveys began in 1986 and continued until 1993 by means of dose rate measurements and soil and vegetation sampling.

The sampling units were marked and numbered (see Fig. 8.10). Standard schematic maps with a scale of 1:10 000 and 1:25 000 were used, while maps with a scale of 1:5000 to 10 000 were used on irrigated (drained) land. The cartograms of contamination of fields in each farm were thus created, which allowed the most contaminated land to be excluding from agricultural use. Based on the cartograms of terrestrial contamination density, the agricultural fields were divided into groups shown in Table 8.2.

8.1.4.2. Arable land

The dose rate measurements were performed by personnel walking along 50–100 m routes. One composite sample was taken from one field during one crop rotation. Soil sampling was carried out using samplers (drills) with a known sampling area (typically 4–5 cm in diameter). Soil samples of arable land that were cultivated after the accident were taken from the ploughed layer (≥20 cm) and unploughed layer (10 cm). Composite samples (1500–3000 cm^3) comprised several subsamples collected from each sampling unit. The number of subsamples (individual samples) depended on the diameter of the soil corer but was not fewer than five samples. In the absence of dose rate measurements, one composite sample was taken from 100 ha.

Ten or more individual soil samples were taken from each 5–25 ha arable land sampling unit before spring cultivation. Samples were taken at equal distances on diagonals and in the centre of the site. At each point, the external dose rate was measured at a height of 1 m and 2–4 cm above the surface. If the dose rates measured at 1 m differed to that near the surface, the sampling point was excluded from the sampling schema. From each sampling site, the individual soil samples were pooled to form a 2 kg composite sample.

FIG. 8.10. Location of sampling units on (a) the farm and (b) cartograms on ^{137}Cs soil contamination.

Vegetation samples were collected at the same locations as the soil samples. For a composite sample of vegetation with a fresh weight of 0.5–1 kg, 8–10 sampling points were selected. The sample could contain all above ground parts or certain parts of the plant (e.g. stems, leaves, fruits, grains or roots). The part of grass above ground was cut with a sharp knife or scissors, removing soil particles, and then it was placed into a plastic bag or paper wrap and labelled. Labels were made of cardboard or paper and bore information on the crop, phase of growth, region, district, division, agriculture, crop rotation number, selected part of plant, date of sampling and name of the person. The underside of the plants was usually contaminated with soil. In this case, the sample was taken above the contaminated parts of a plant, or the sampled material was washed with clean water prior to packaging.

Homogeneously contaminated fields or some parts of the fields where only one culture was grown were selected as sampling units. Such sites were chosen to be representative of the affected area according to soil types, relief elements and type of agricultural use.

Every sample selected comprised ten or more individual samples, collected uniformly from the entire sampling unit area. When sampling with a borer, the number of puncture samples required depended on the diameter of the borer. When sampling with a spade, the sample was taken to the depth of the cultivated or ploughed layer. All samples collected in the sampling unit were homogenized; and with the quartering method, a sample (≥2 kg) was selected from the total mass of the composite sample, placed into a plastic bag, which was placed into a second plastic bag and then wrapped in hard paper. Each sample was accompanied by a chain of custody form placed between the plastic bag and the paper cover.

At fruit and berry sites, samples collected from the whole garden or from the whole crop were quartered, with every part representing a sampling unit. The individual samples were collected from the entire depth interval of primary cultivation, and the composite sample was prepared as describe above.

8.1.4.3. Uncultivated farmland

The objective of sampling uncultivated farmland (e.g. meadows, pasture and grassland) is to evaluate its farming potential. The collection of representative samples was similar to that used in the settlements:

— External dose rate measurements were taken along the perimeter and in the diagonals of the monitored site.
— Soil sampling was conducted with the rings at five points of the sampling unit.

On grassland and pasture, the sampling unit size was approximately 10 ha. In the first five years after the accident, soil samples were collected from the top 5 cm of a mown plot. The sampling depth was then increased to 10 cm to account for migration within the soil profile. At locations with potentially elevated migration, such as peat soils, the sample depths were taken separately from two soil layers (0–10 cm and 10–20 cm). Where necessary, soil samples at the central point of a sampling unit were collected at depth intervals of 0–2, 2–5, 5–10 and 10–20 cm to determine their vertical distribution. Identification of virgin areas (i.e. where the soil had not been ploughed since the accident) was made based on prior measurements of the external gamma dose rate, which were then compared with those from neighbouring arable land. Sites were preliminary assigned as virgin soil if the exposure dose rate was 1.5–2 times higher than that of arable soil.

The number of individual samples taken at each sampling unit depended on the sampling equipment: there were 24 individual samples for the 50 mm diameter drill and over 30 individual samples for the 40 mm diameter drill. The total weight of the samples was 8 kg. After a thorough mixing and homogenization of the composite sample, one sixth was taken for the sequent measurements; the rest was discarded.

Vegetation sampling was conducted along with soil sampling. At a sampling site, 8–10 isolated 1 m × 1 m or 2 m × 2 m areas were chosen, arranged diagonally. Grass (hay) was cut with a scythe, sickle or other cutting tool at 3–5 cm above the ground. Green vegetation from all points or areas were collected, mixed thoroughly and spread into an even layer to form a composite sample. From this, a 1.5–2 kg composite sample of 150–200 g portions from different places was prepared for analysis.

For grass, a sample was obtained from a 1 m^2 plot at the sampling point, 3 cm above the surface. Where grass yield was low, the sampling area was increased to obtain a mixed 2 kg sample. Composite samples were wrapped in hard paper and labelled. The number of grass samples was the same as for soil samples. Information on the culture, vegetative stage, sampling area (for grass and cereal) and the number of the collected plants was recorded in the field notebook.

8.1.5. Forested areas

Two types of sampling programmes were implemented in contaminated forests after the accident at the Chernobyl nuclear power plant. The purpose of the first sampling programme was a survey of the forest soil to assign different contamination zones to make further decisions on the management of the contaminated forest. Overall, these zones were the same as those given in

Table 8.2 with the exception that two subzones (37–74 kBq/m^2 and 74–185 kBq/m^2) were considered instead of the 37–185 kBq/m^2 zone. This additional detail was included to account for specific patterns of caesium transfer to some forest products (see Fig. 8.11).

The main method used for conducting the radiation surveys in forests was the collection of composite soil samples in the forest units (quarters) followed by the determination of contamination density by measuring each composite sample. Sampling of wood was carried out within the forest units to verify that the wood contamination was in compliance with the permissible levels. A special long term monitoring programme was designed to identify trends in changing ^{137}Cs activity concentrations in forest compartments such as genetic horizons of the forest soil, wood and other forest tree compartments, mushrooms, berries and other understory species.

8.1.5.1. External dose rate measurement during initial survey and selecting sampling units

Sampling units were selected based on an evaluation of the forest quarters used in normal forestry. The quarters represent forested areas demarcated by the forest cuttings or other natural or artificial boundaries. The forest quarters are permanent units of the forestry service. In lowland areas, forest quarters are

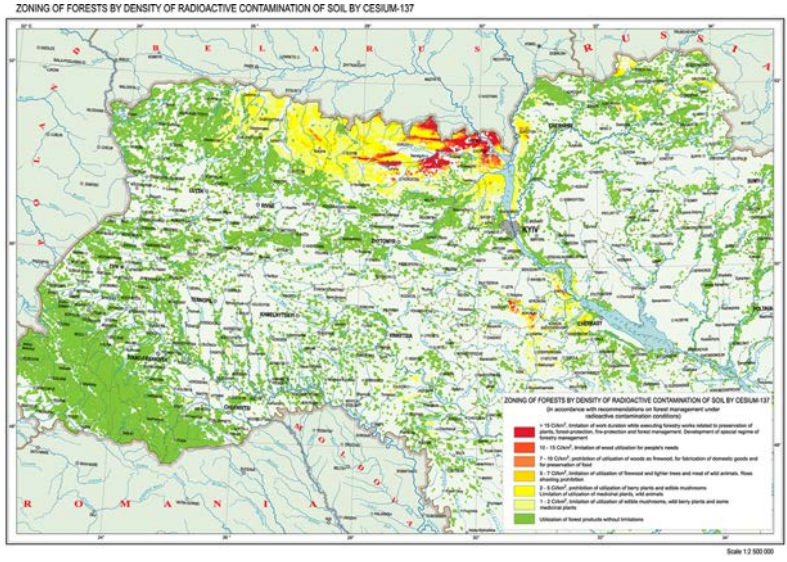


FIG. 8.11. Zones of ^{137}Cs contamination in forest in Ukraine [8.13].

rectangular or square in shape, approximately equal in size and are separated by quarterly cuttings, which are cut through, as a rule, from north to south and from east to west. In the mountain forests, the border blocks are often mountain ridges, gorges, rivers and roads. These forest quarters are irregular in shape and often consist of a combination of quarterly glades with natural boundaries. They also vary considerably in size (50–800 ha) depending on the forest inventory, such as tree composition and age, the type of understory and the properties of the forest soil. Sampling units were considered to be the same as quarters if the contamination was homogeneously distributed or were assigned to forest quarters with similar contamination levels.

The initial sampling approach in Belarus, the Russian Federation and Ukraine was based on the combined measurement of the external dose rate (initial survey) and the soil sampling. Forest contamination was mapped by measuring the dose rate and soil samples from each forest unit (see Fig. 8.12).

To assess contamination inhomogeneity of the forest quarter, the external dose rate was measured in 20 or more points located evenly at the perimeter

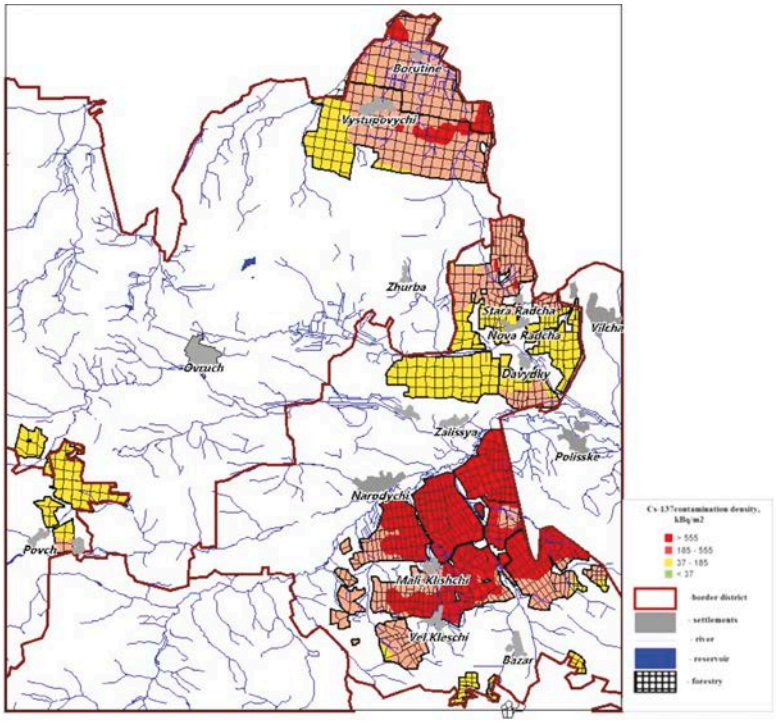


FIG. 8.12. Density of ^{137}Cs contamination in the forest of the Zhytomyr region.

of the forest quarter at a height of 1 m above the ground. The measurement points were selected at a distance more than 10 m from the borders of the forest quarter. Three or more measurements were made at each measurement point. The arithmetic mean of these measurements was determined and reported as the value corresponding to the measurement point.

The mean, minimum and maximum values for the forest quarter were calculated based on data for all measurement points within any quarter. The forest quarter was considered as homogeneously contaminated — and hence was taken as a sampling unit — if the ratio of the maximum external dose rate to the minimum external dose rate was less than 3.3; otherwise, the forest quarter was considered inhomogeneously contaminated and 10–15 additional measurement points evenly distributed within the quarter were selected. Each such type was further considered as an individual sampling unit.

8.1.5.2. Forest soil sampling

A network of stationary sites was created for the continuous monitoring of radionuclides in forest production. The external gamma dose rate at a height of 1 m above the ground and the density of a flux of beta particles from the ground surface were measured. Results were released in the form of quarterly coloured schemes of radioactive contamination.

Samples were taken not closer than 30–50 m from roads, edges of forests and glades, and the banks of rivers and lakes. It was recognized shortly after the accident that the more that time passed from the initial contamination, the greater the depth was required (up to 1 m in 2016). All samples were supplied with labels and were documented. One composite sample of litter and mineral soil was taken from each sampling unit (forest quarter or its part). The soil sample had a diameter of 4 cm and a depth of 15–20 cm. One composite 1 dm^3 sample was created from five individual samples. Individual samples were selected following the envelope method — on corners and in the centre of the quarter (see Fig. 8.3).

A modified approach was used in Belarus for long term monitoring. A 30 m × 30 m area was selected within the sampling unit with the following requirements:

— There should be a deviation lower than 10% of the external gamma dose rate measured within the area from that measured for the sampling unit.
— Secondary redistribution of radionuclides within the area should be negligible.
— A composition of dominating trees and understory species should be similar (on average) to those in the sampling unit (i.e. forest quarter or its part).
— The other procedures are similar to those described above.

8.1.5.3. Forest vegetation sampling

Sampling of vegetation (structural components of the stand, shrubs, grasses, mosses and mushrooms) were carried out annually by special samplers. Wood, bark, branches, leaves and pine needles were collected by the standard method of model trees [8.16–8.18]. Model trees were selected for each of the main tree species on the mean diameter and height. For each tree wood sample, bark, small twigs, pine needles (leaves) and fruits (seeds) were sampled. Samples of wood, bark and phloem were selected from the butt, middle and apical parts of the trunk.

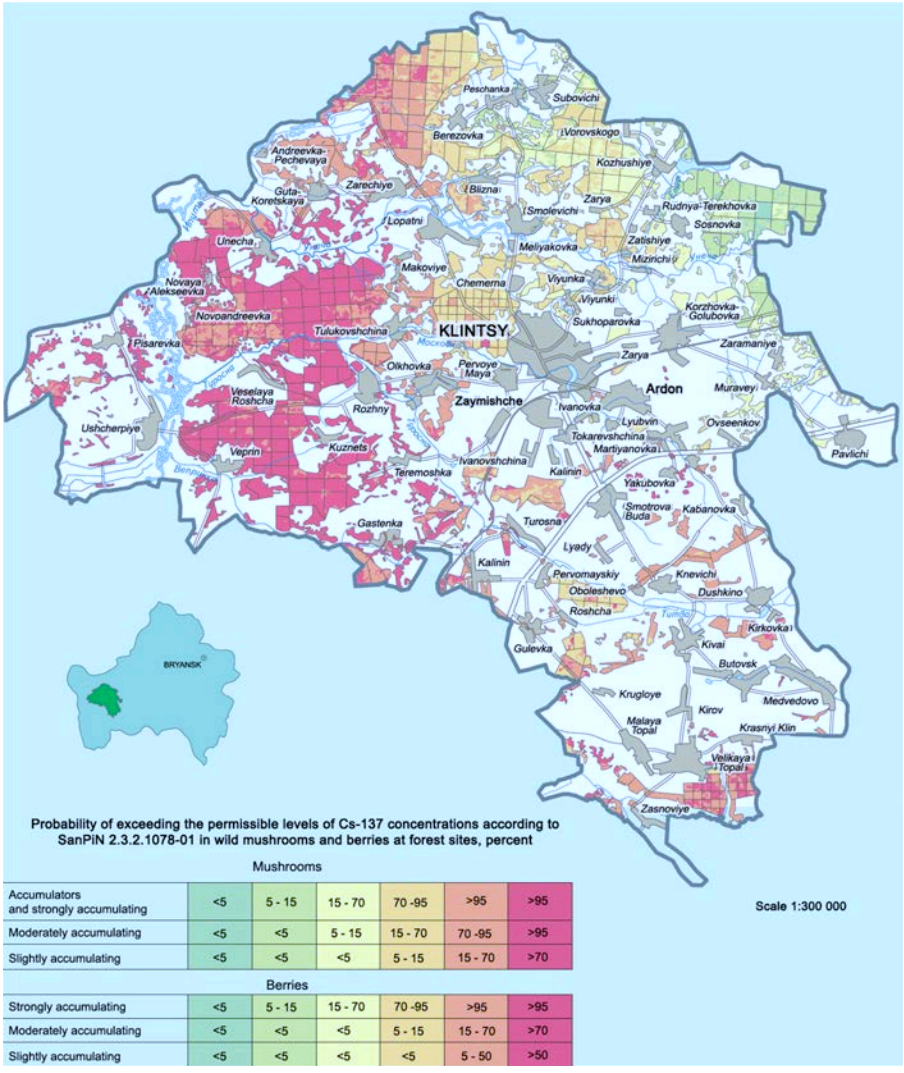
After felling, pine needles, leaves and twigs were collected from various layers of the crown. The trunk was sawn into lower, middle and upper sections. After removal of the bark, the sample was homogenized and an average sample in the form of wood chips was taken of the trunk.

Samples of mushrooms and berries were selected within a single highlight or quarter. Mixed samples of fungi were collected from three groups based on their radionuclide accumulation ability (i.e. low, medium and high accumulation of radionuclides). Mixed samples consisted of the most represented species of mosses, grasses and berries. The grass cover, bushes and undergrowth were cut with a knife, shears or scissors at a height of not less than 3 cm from the soil surface. An averaged sample comprised at least 8–10 individual samples. Based on this sampling programme and consequent measurements of radionuclide concentrations in the forest compartments, the contamination of forest products was mapped to optimize forest management (see Fig. 8.13).

8.2. SAMPLING PROGRAMMES IN THE AREAS AFFECTED BY THE ACCIDENT AT THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANT

8.2.1. Soil sampling for mapping fallout in nuclear emergencies

The accident at the Fukushima Daiichi nuclear power plant occurred after the Great East Japan Earthquake on 11 March 2011, which resulted in the release of significant quantities of radionuclides such as ^{134}Cs, ^{137}Cs and ^{131}I [8.19]. Onda et al. [8.20] report on the soil sampling strategies, beginning with a rapid soil survey urgently requested by the Science Council of Japan. Soil samples within a 30 km radius of the plant and an emergency soil sampling protocol were requested to evaluate radionuclide contamination levels and any possible effects on human health. Onda et al. [8.20] identify several challenges for sampling and sample preparation protocols:



Mushrooms

Accumulators and strongly accumulating	<5	5 - 15	15 - 70	70 -95	>95	>95
Moderately accumulating	<5	<5	5 - 15	15 - 70	70 -95	>95
Slightly accumulating	<5	<5	<5	5 - 15	15 - 70	>70

Berries

Strongly accumulating	<5	5 - 15	15 - 70	70 -95	>95	>95
Moderately accumulating	<5	<5	<5	5 - 15	15 - 70	>70
Slightly accumulating	<5	<5	<5	<5	5 - 50	>50

FIG. 8.13. Mushroom contamination for optimizing forest management based on data from the forest sampling programme.

— Very few standardized soil sampling protocols can process very large numbers of samples to measure gamma emitting radionuclides.
— Sufficient sampling equipment is difficult to obtain in emergency situations.
— Any potential sampling protocol needs to be simple to ensure consistency across sampling teams.
— Compared to ^{134}Cs and ^{137}Cs, few published data exist on direct measurements of ^{131}I contamination.

On account of its fast accumulation in the thyroid, ^{131}I can deliver a relatively high radiation dose to exposed individuals in a short period of time. It can be transferred to humans through, for example, milk from animals grazing on contaminated pastures. However, the technical difficulties involved in measuring ^{131}I activity soon after release into the environment is because of its relatively short half-life of eight days. Onda et al. [8.20] explain:

> "Thus, no protocol was available for investigating soil contamination by ^{131}I fallout immediately after the reactor accident.
>
> "Therefore, we adapted a plastic cylindrical container (U-8;...50 mm inner diameter and 60 mm height), which is widely used for the measurement of gamma-rays in environmental samples in Japan, for use as a soil collector and also as a container during measurements. We then used the resulting protocol to collect 2200 soil samples (Saito et al. [8.21])."

A summary of the sampling programmes implemented after the Fukushima Daiichi accident is given in the Annex, and includes the sampling programme objectives, the types of sampling and equipment, and references to additional literature.

8.2.2. Establishment of the emergency soil sampling protocol

8.2.2.1. Depth distribution of radionuclides

Kato et al. [8.22] study the depth distribution of radionuclides in surface soils with a 15 cm × 30 cm scraper plate (see Fig. 8.14):

> "The scraper plate has two components; a metal frame that is placed on the ground, and an adjustable metal plate that can scrape or remove fixed increments of soil-depth within the frame. Advantages of the device is following; it provides a large volume of material from a large surface area, and it has few moving parts and it is robust and of simple construction....

Samples were taken with 0.5 cm increments for the depth of 0–5 cm and 1.0 cm increments for the depth of 5–10 cm, and 2.0 cm increments for the depth of 10–30 cm. In order to avoid contamination by the surface soil which can fall down from the wall of the sampling hole, spray glue was used to fix the wall. The sampled soil was then shipped to the laboratory, placed in a plastic container and sealed without oven drying and sieving to avoid ^{131}I release into the atmosphere."

Kato et al. [8.22] plot the depth distributions in the topsoil of ^{131}I, ^{134}Cs and ^{137}Cs concentrations (see Fig. 8.15) and find that:

"The maximum concentration was found at the surface for all the radionuclides and the concentrations exponentially decreased with depth.

Note: Scraper: 5 mm increment to 10 cm, and 1 cm increment to 30 cm.

FIG. 8.14. Scraper plate for collection of soil samples for depth profiles of nuclides. (Courtesy of Yu. Onda, Tsukuba University, Japan.)

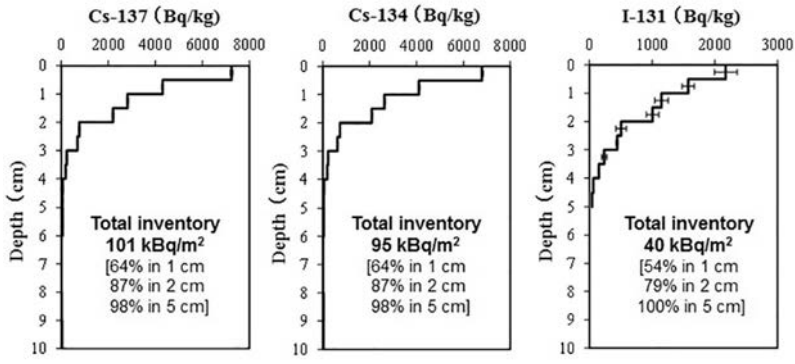


FIG. 8.15. Depth distribution of ^{137}Cs, ^{134}Cs and ^{131}I activity concentrations [8.22].

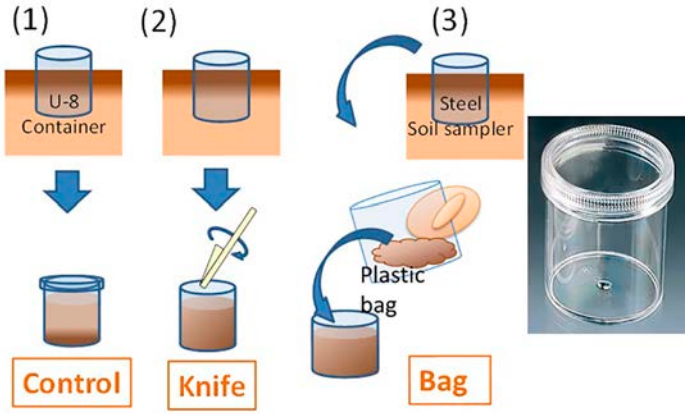
"...Approximately 80% of the deposited radionuclides were found in the upper 2 cm of the soil. Sixty-three percent of total radioactivity inventory for both radiocaesium and 54% of total ^{131}I were contained in the top 1 cm. Furthermore, 86% and 96% of total radiocaesium inventory were absorbed by soils above 2 cm and 5 cm depth, respectively. For ^{131}I, 79% of total radioactivity inventory in the soil profile was contained in the top 2 cm, and all ^{131}I existed within the soil above 5 cm depth."

8.2.2.2. A preliminary study of soil collection methods

Based on the fact that most of the ^{131}I, ^{134}Cs and ^{137}Cs activities are contained within 5 cm of the surface, Onda et al. [8.20] assume:

"...the radionuclide deposition flux resided in the surface soil layer (within 5 cm of the soil surface) during the collection period (June–July 2011). Therefore, we used 100-mL U-8 containers...outfitted with calibration radiation sources; the samples were placed in these containers so as to homogenize the radioactive material contained in the soil. It was important not to heat soil samples containing ^{131}I since because drying the soils could cause ^{131}I to evaporate and disperse into the laboratory. However, air-drying would be time-consuming with such a large number of samples, and we therefore measured wet soil samples sealed in the field (e.g., Kato et al. [8.22]). To evaluate the accuracy and precision of the measurement of radionuclide concentrations in soil samples with a germanium detector, we undertook a preliminary test of the following three potential methods (Fig. [8.16]):

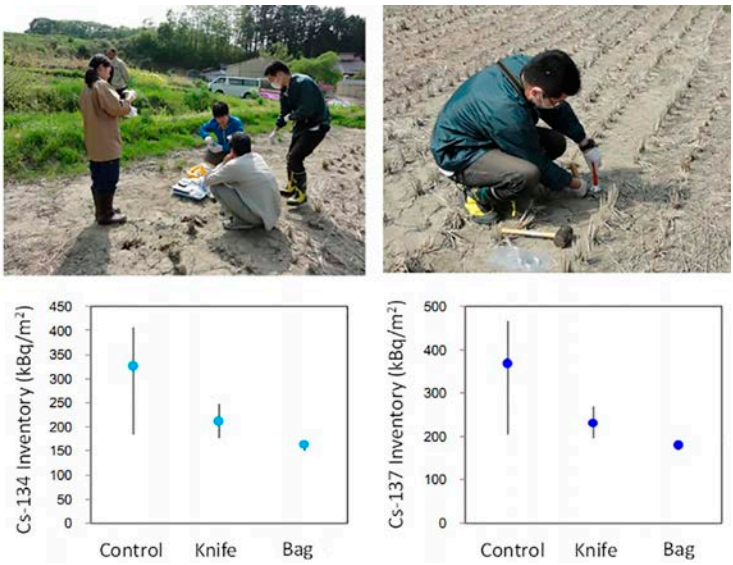
1) Unmixed soil (control): Soil was collected by inserting a U-8 container into the surface soil layer and left unmixed. Radioactivity concentration was then measured.
2) Stirred soil: Soil was collected by inserting a U-8 container into the surface soil layer, after which it was stirred with a disposable plastic knife and vibrated 150 times (see Fig. [8.16]) after sealing. Radioactivity concentration was then measured.
3) Homogenized soil: Soil was collected by inserting a U-8 container into the surface soil layer, after which it was placed in a polyethylene bag and shaken. The soil must be loosened through pressing and crushing by hand if any aggregated soil remains after shaking. Finally, the sample was transferred back to a U-8 container for storage and the radioactivity concentration was measured."



Source: Figure 1 of Ref. [8.20] (left).
Note: The terms 'Control', 'Knife' and 'Bag' indicate no treatment, mixed with a knife, and mixed in a plastic bag by hand, respectively. Five soil core samples were collected from the forest floor, grassland and paddy field on 21 May 2011.

FIG. 8.16. Schematic diagram of the three sampling procedures.

"Fig. [8.17] shows ^{137}Cs concentrations obtained using the three mixing techniques for samples collected in a paddy field in the Yamakiya region, Fukushima Prefecture (sampled on May 21, 2011). Our preliminary tests showed that soil samples collected from paddies and grasslands measured using method 1, in which the distribution of radionuclides in the sample was not uniform, produced some measurement errors arising from the application of a calibration gamma source that assumed a homogeneous distribution of radionuclides, while stirring the samples as in method 2 allowed soil to spill from the containers. Measurement variability was less than in method 1, but a scatterplot indicated that samples were still not sufficiently homogenized. Fig. [8.17] clearly indicates that soil mixed outside the containers, as in method 3, was in an adequately homogeneous state and radioactivity concentration measurements had little statistical scattering. Using these results, we decided to use method 3, stirring the sample in a polyethylene bag, for further soil collection."



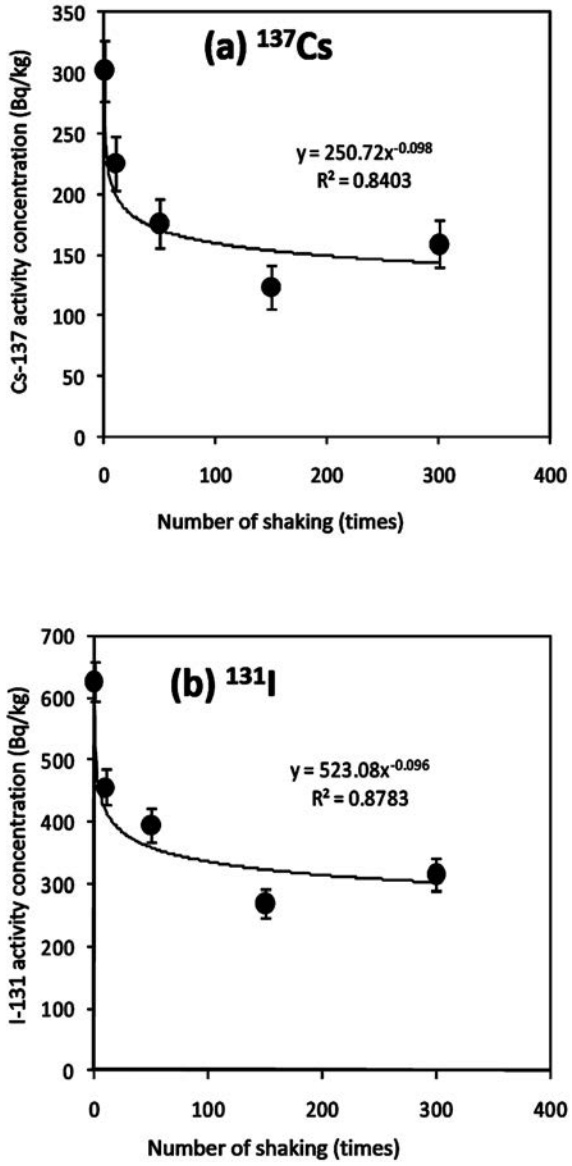
Source: Figure 2 of Ref. [8.20].
Note: Refer to Fig. 8.16 for each treatment. Error bars denote the range of measured radioactivity in the five soil samples. Soil core samples were collected on 21 May 2011.

FIG. 8.17. Effect of mixing method on the measured radioactivity in soil samples (paddy field).

Figure 8.18 provides the relationship between the number of times that the sample was shaken and the measured concentration of ^{137}Cs and ^{131}I. Soil sampling was conducted in April 2011 on an artificial hillslope at the Terrestrial Environmental Research Centre of the University of Tsukuba. The shaking treatment was performed reciprocally by several operators to correct individual differences. Results indicate that shaking samples at least 150 times is necessary to homogenize soil materials in the containers.

8.2.2.3. Selection of soil collection locations

Onda et al. [8.20] emphasize that collecting multiple samples from the same locations is vital to monitor long term changes in the fallout inventory of radioactive material. To achieve this, they selected sampling locations with no anticipated disturbances. They tried to choose sampling points without vegetation, and they collected five soil samples from each site within a range of 3 m of each other to account for any anticipated variation in soil radioactivity concentrations. In some cases, soil core samples were collected together with above ground vegetation, and where "sampling locations fell inside high-radiation dose-rate



Source: Figure 8 of Ref. [8.20], modified.
Note: Soil sampling was conducted on an artificial hillslope at the Terrestrial Environmental Research Center of the University of Tsukuba, Japan, on 16 April 2011.

FIG. 8.18. Effect of shaking on the measured concentrations of ^{137}Cs and ^{131}I.

areas (e.g., evacuation zones), only one to three samples were taken to avoid prolonged exposure of sampling workers to radiation" [8.20].

8.2.3. Protocol for assessing radionuclide contamination in soil samples

8.2.3.1. General information

Onda et al. [8.20] recommend the following:

"1) Select sampling locations and points: Flat topography is preferable to minimize the effects of the redistribution of radionuclides. Verify that the terrain is flat and that no large obstacles (such as vehicles or buildings) exist within a 5 m range of the sampling location. Open areas, such as croplands or paddy fields, are preferred, and forested areas should be avoided as most of the fallout is trapped in tree canopies. Paddy fields can be used before irrigating (Takahashi et al. [8.23]).
2) Soil and land cover maps are useful for designing a sampling strategy (location and density of sampling points) since soil types and land uses can influence the extent of radioactive contamination in soils.
3) The geographic position of each sampling point within each location should be recorded using a global positioning system (GPS).
4) Use protective clothing and gloves for handling soil samples."

8.2.3.2. Soil sampling and analysis

Figures 8.19 and 8.20 detail the procedures for soil sampling and laboratory analysis. Onda et al. [8.20] recommend the following:

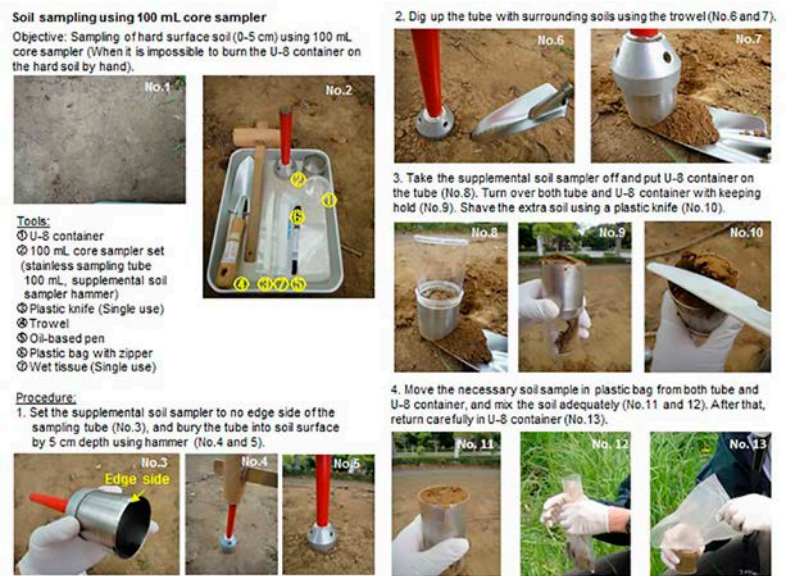
"Disposable gloves should be used to avoid cross-contamination.

1) Five soil samples, 5 cm deep, should be collected within a 3 × 3-m^2 area at the selected sampling location. Ideally, we recommend the four corners and center of the square as sampling points. The depth is recommended because most of the recent and current radioactive contamination remains in this layer (Kato et al. [8.22]; Ohno et al. [8.24]).
2) The total area of soil sampled (98 cm^2) when taking five samples is sufficiently larger than the 50-cm^2 sampling area suggested by Khomutinin et al. [8.11].

Source: Figure 6 of Ref. [8.20].

FIG. 8.19. Emergency procedure for the investigation of radioactive contamination of the soil using the U-8 container.

3) Measure the ambient equivalent dose rate (μSv/h) using a portable dosimeter at a height of 1 m. At all locations, slowly move the survey meter 3 m in all directions from the center to confirm the absence of any singular points with sudden spikes in air-dose rates.
4) Try to locate sites with open space, and if possible, areas not covered by vegetation. Do not remove small fragments of leaves and organic layers because they may contain ^{137}Cs and ^{134}Cs. ...
5) Soil samples can be collected using one of two methods:
    1) ...Each U-8 measurement container should be weighed before sampling and clearly marked. Insert the U-8 container gently into the soil and use it as a scoop. Cut the surface with a disposable plastic knife and mix well in the plastic bag before sealing.
    2) Using a core sampler for hard soil...50 mm in diameter.... The samples should be placed in plastic bags, and then mixed well by shaking the outside of the plastic bag and packed into U-8 containers (when using a 100-mL core sampler). Metal samplers can be used at the same sampling site after cleaning with alcohol in situ, but never use the same sampler for different locations to prevent cross-contamination. Samplers should be cleaned after returning to the lab.



Source: Figure 7 of Ref. [8.20].

FIG. 8.20. Emergency procedure for the investigation of radioactive contamination of compacted soil using the 100 mL soil core sampler.

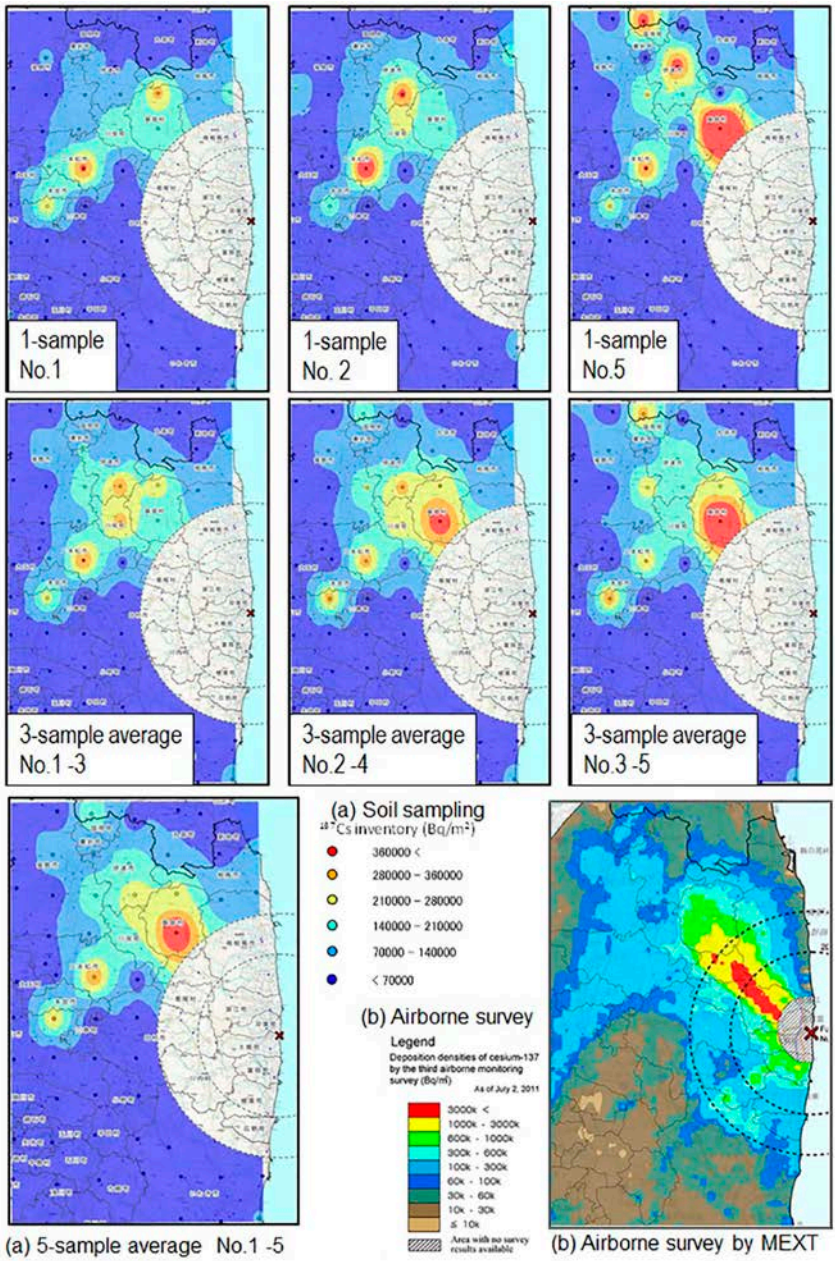
3) Soil water content may be measured in the field using a portable time-domain reflectometer (TDR). This procedure is optional if oven-drying is impossible due to the need to avoid iodine sublimation at higher temperatures.
4) Because of the possible spatial variability, all five soil samples should be measured. All sampling containers should be properly labeled with weight, soil depth, GPS reference number, and land-use type, and hermetically sealed. Wipe the outside of the container with alcohol-impregnated tissue paper to decontaminate and take a photograph to distinguish the soil color and type.
5) Each sample should be placed inside a new plastic bag and zip-locked by a person who has not touched the soil (expected to be uncontaminated). The five samples from each location should also be zip-locked in a larger bag and transported to a laboratory in secured containers labeled with radioactive signs.
6) The national radiation safety regulations should be observed at all times (i.e., do not exceed 5 μSv/h at the surface of the transportation container as proposed in the Japanese L package standard).

7) In the laboratory, information regarding GPS coordinates (region, latitude, and longitude), land use, soil types, digital photographs, sampling dates, and other relevant comments should be entered into a computer database.
8) The U-8 soil containers should be sealed again in zip-lock bags or plastic film by two persons (one person to touch the container, and another to cover the container without touching its surface), to avoid contamination of the Ge-detector.
9) The bulk density should be calculated using net sample weights and field soil moisture contents. If oven-drying is possible (i.e., ^{131}I level is low), soil can be dried and the bulk density can be calculated.
10) To convert the amount of radioactive contamination per kilogram of soil to the amount of radioactive contamination per 1 m^2 of land (Bq/m^2), average the radioactive contamination (Bq/kg soil) and the bulk density values of the five subsamples.
11) Before measurement, the sample container should again be shaken well to mix the large amounts of ^{137}Cs in the surface soil. ...
12) Given the expected high concentrations of radionuclides, the counting time will be limited by the counting statistics error of ^{137}Cs, ^{134}Cs, and ^{131}I, which should be a maximum of 5% (ideally 3%)."

8.2.3.3. Results of preliminary sampling

The spatial pattern of the ^{137}Cs inventory after the Fukushima Daiichi accident (see Fig. 8.21) is based on the emergency soil sampling protocol. Onda et al. [8.20] propose the following:

> "Five soil samples (No. 1–No. 5) were collected within a 3 m × 3-m area at each sampling site (56 sites in total). The influence of the number and combination of samples at each site in the ^{137}Cs inventory mapping results are discussed below.
>
> "Our map shows unfavorable variation in the ^{137}Cs inventory when a single soil sample is selected from the five. In maps based on soil samples No. 1 and No. 3, an area with a relatively high ^{137}Cs inventory, appearing northwest of the reactor in the soil sample No. 5 map, is missing. Using multiple samples reduces the differences in ^{137}Cs inventory patterns among maps, but large inconsistencies still exist among maps based on combinations of three regularly selected soil samples. Finally, the ^{137}Cs inventories of the five soil samples were averaged and used to produce an inventory map. The spotlike distribution of the ^{137}Cs inventory was



Source: Figure 9 of Ref. [8.20].

FIG. 8.21. Influence of the number of samples at each sampling site on the ^{137}Cs inventory mapping results.

averaged when the five samples were combined and the resulting map is largely consistent with the results of the Third Airborne Monitoring Survey of Radioactivity (MEXT [8.25]).

"The results of this study indicate that collecting and combining at least five soil samples within a 3 m × 3-m area is the minimum number required to produce a precise fallout inventory map of radionuclides from the FDNPP accident. The emergency sampling protocol proposed in this study should be considered in case of emergency situations following nuclear hazards."

8.2.4. Major soil sampling campaign

8.2.4.1. Preparation of the large scale mapping project

A manual was prepared before sampling for training on the necessary operational procedures and radiation protection measures. Each team comprised a minimum of two people, ideally with at least one experienced worker.

For soil collection locations, air dose measurements at 1 m above the ground were made using a unified measurement system and general purpose radiation measuring instruments, and a large number of workers were substituted throughout the process. Measurements were generally performed using a NaI(Tl) scintillation spectrometer. Where the air dose rate exceeded 30 μSv/h at 1 m, an ionization chamber survey meter was used instead. The entire calibration test history of each spectrometer or dosimeter used for measurement was checked and recorded.

Sampling sites with scarce vegetation were selected because radioactive material attaches to the vegetation canopy. Similarly, forested areas were also avoided. At the selected locations, the survey meter was slowly moved in a 3 m range in all directions from the centre of the spot to confirm the absence of any singular points with sudden changes in the air dose rate. For example, since radionuclides can accumulate in the soil of ditches or underneath downspouts carrying rain water, the air dose rate was not measured in those types of location.

The location of each investigation site was recorded using a GPS device and checked by at least two people. For surveys within the 80 km zone outside the Fukushima Daiichi nuclear power plant, a map of four 2 km grid cells was prepared. Each site previously designated by municipalities or scheduled for soil collection was then marked on the map, after which on-site air dose rate measurements and soil collection were conducted. The collected soil samples were transported to the Japan Chemical Analysis Center and the University of Tokyo, which conducted the measurements. The creation and storage of an electronic record of the survey was then verified, after which the investigation site was confirmed as completed (see Fig. 8.22).

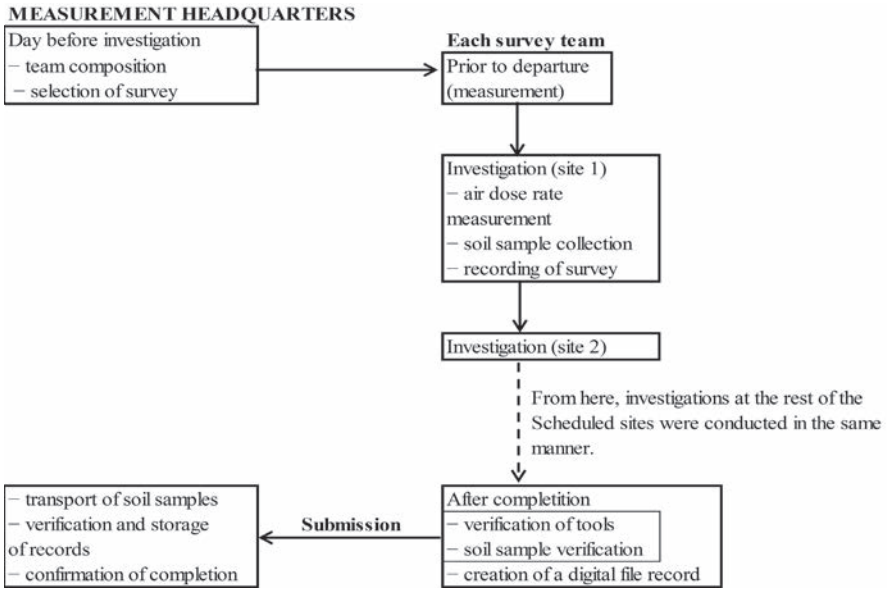


FIG. 8.22. Soil sampling and air dose monitoring flow chart.

8.2.4.2. Selection of sampling locations

In the Saito et al. [8.21] study (see Fig. 8.23):

"The soil sampling locations were selected on the basis of the following criteria. Based on the radiation levels roughly clarified by prior environmental monitoring including air-borne survey (MEXT [8.25]), the sampling locations were selected within a 100 km radius of the Fukushima NPP site and throughout the rest of Fukushima Prefecture. The region within 80 km of the site was divided into 2 km square grids, and the rest was divided into 10 km square grids. A suitable location was chosen within each grid considering the ground condition and other conditions as described below. In the case that two municipalities were in one grid, two sampling locations were selected to cover both municipalities. Non-inhabitable areas were avoided since our direct concern was to check the contamination levels of living conditions.

"Inhomogeneously contaminated locations were avoided in order to obtain sample data representing regional contamination; thus, flat fields of a certain width and little vegetation were selected. The intention was

to continue the periodical environmental monitoring at identical locations to investigate the time-dependent changes in the contamination conditions due to weathering effects. Thus, locations where the geographic conditions were expected not to change for a long period of time were chosen: for example, farm fields were avoided since they would be often plowed. We also avoided riverside locations since floodwaters may significantly change the deposition conditions. With regard to land-ownership, public lands were preferred to private lands, because it was easier to obtain permission for soil sampling.

"Since there was insufficient time to directly check the sampling locations, they were selected by carefully checking maps overlaid 2 or 10 km square grids. After the sampling locations were determined, we obtained permission for soil sampling from all municipalities with related jurisdiction."

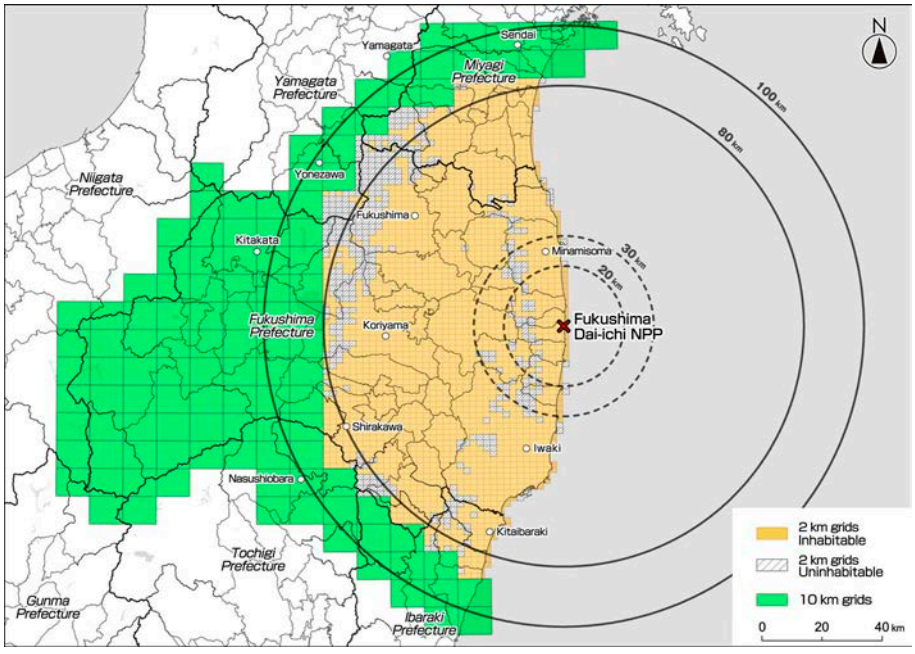


FIG. 8.23. Establishment of a grid for the purpose of selecting investigation sites.

8.2.4.3. Soil sampling project

Saito et al. [8.21] report that:

"More than 400 volunteers from more than 90 organizations took part in the soil sampling from June 4 to July 8, 2011. ... Each soil sampling team had two or three members including at least one specialist in radiation or radioactivity. Each team collected soil samples at several locations per day. Every day, up to 30 teams were engaged in soil sampling. In the 20 km zone where entry was restricted, we asked the Federation of Electric Power Company of Japan, which was responsible for routine monitoring in the zone, to support the soil sampling.

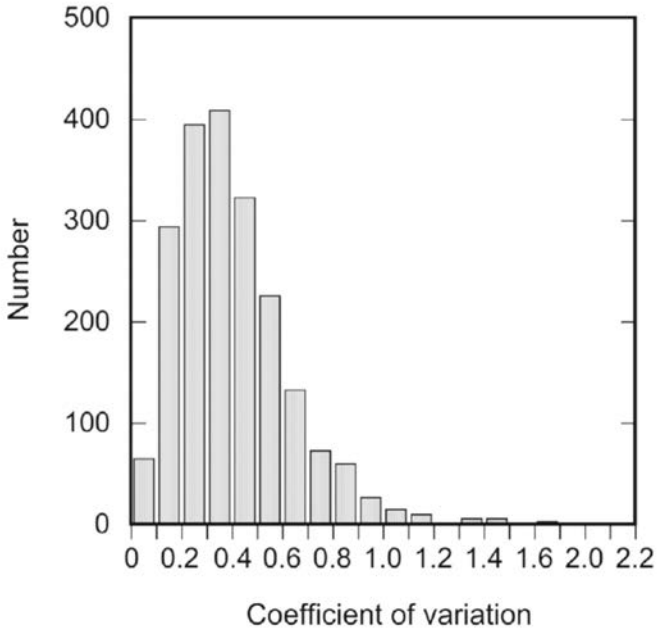
"...In the campaign, all of the soil sampling and spectrometry were carried out according to the protocol. Some of the planned sampling locations could not be reached because the access roads had been severely damaged by the earthquake or tsunami. Overall, soil sampling was performed at 2138 locations.

"...the surface soil was dug up to 5 cm depth.... At locations where sampling was not easy [due to the high dose rate], soil samples less than five were collected. In total, 10,915 soil samples were collected."

8.2.4.4. Data analysis

Saito et al. [8.21] find that the variation coefficient of the caesium radioactivity concentrations for the five soil samples collected at one location varied with an average of 36% (see Fig. 8.24):

"Radioactive nuclides ^{134}Cs and ^{137}Cs were detected at every sampling location. In other radioactive nuclides, statistically significant data were obtained from soil samples at a limited number of locations.... When statistically significant data were obtained for at least one soil sample at one location, deposition was judged to have occurred at the location, and the average deposition density was estimated."



Source: Figure 14 of Ref. [8.21].
Note: The coefficient of variation represents the ratio of the standard deviation to the mean. The number of soil sampling locations within a certain range of the coefficient of variation is shown by a bar graph.

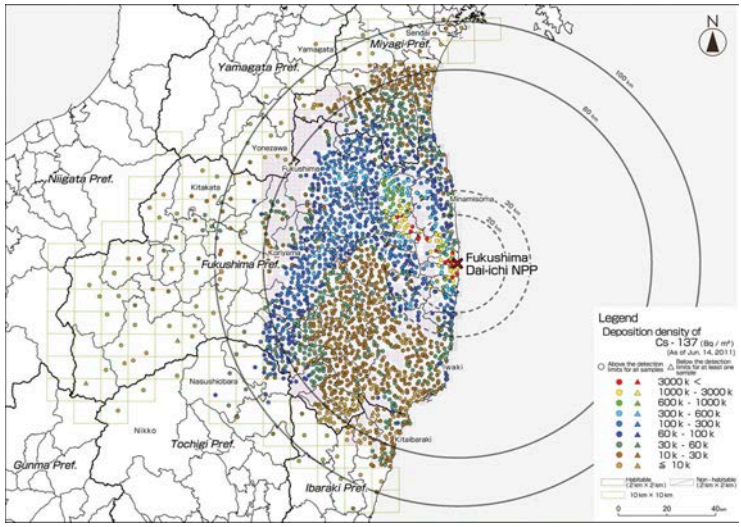
FIG. 8.24. Statistics on coefficients of variation for ^{137}Cs concentrations among five soil samples collected at one location.

8.2.5. Development of the contamination density map

Figures 8.25 and 8.26 map deposition densities of ^{137}Cs and ^{131}I. Saito et al. [8.21] describe that:

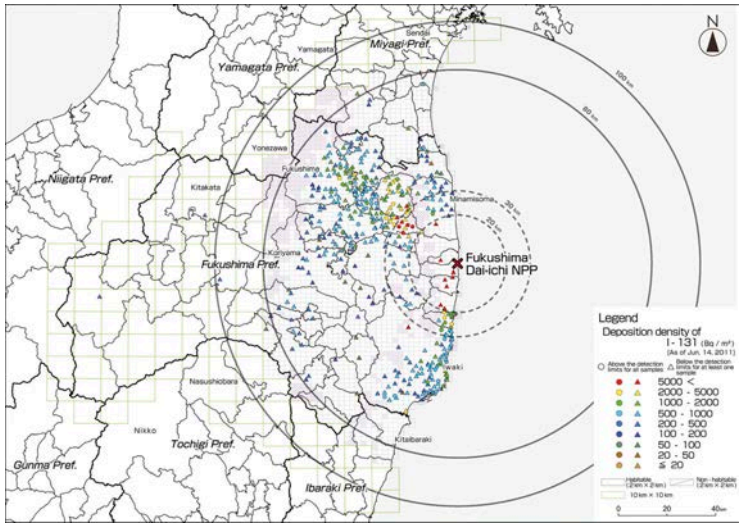
> "The radioactivity per unit ground area (Bq/m^2) on June 14, 2011 is indicated by a colored mark at the soil sampling locations. The major soil sampling campaign was completed on this date; thus, all radioactivities were corrected to this day based on the decay half-life of the corresponding nuclide."

The sampling and subsequent measurements for the deposition density map for ^{131}I started on 6 June, resulting in limited data for ^{131}I. However, this data could provide useful information of the ^{131}I deposition density for estimating



Source: Figure 2 of Ref. [8.21].
Note: The radioactivity per unit ground area is shown by the coloured mark at the soil sampling location.

FIG. 8.25. Deposition density map for ^{137}Cs.



Source: Figure 3 of Ref. [8.21].
Note: The radioactivity per unit ground area is shown by the coloured mark at the soil sampling location.

FIG. 8.26. Deposition density map for ^{131}I.

the radiation exposure to local residents. Saito et al. [8.21] also mapped ^{134}Cs, ^{110m}Ag and ^{129m}Te. Maps of ^{231}Pu and ^{90}Sr have been developed based on selected samples from the large soil sampling campaign.

Figure 8.27 provides a comparison of the ^{137}Cs inventory in the soil samples and inventory obtained from airborne monitoring. These plots are used to determine the effective relaxation mass depth β_{eff} (defined as a relaxation mass depth of an equivalent exponential function giving the same air kerma rate at 1 m above the ground as the inventory [8.21]) of airborne monitoring from the best fit. Although the soil samples from the 80 km radius were taken, the range of ^{137}Cs inventories varies between less than 10 kBq/m^2 to more than 60 MBq/m^2. The conclusion can be made based on the comparison that the airborne monitoring data in Japan after the Fukushima Daiichi accident were very accurate.

8.2.6. Emergency soil sampling performed by other agencies

In addition to the sampling by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), several other governmental agencies have also conducted soil sampling to create maps (see Annex). In farmland and paddy fields, the Ministry of Agriculture, Forestry and Fisheries (MAFF) has mapped the soil contamination density area affected by the Fukushima Daiichi accident

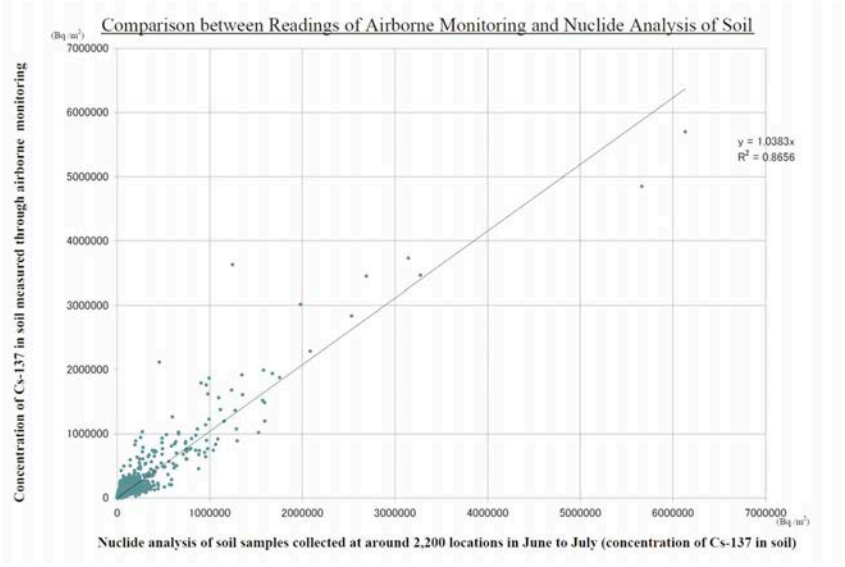


FIG. 8.27. Comparison between readings of airborne monitoring and nuclide analysis of soil [8.21].

to establish the caesium concentration in cultivated soils to determine the extent of decontamination required in agriculture fields and to consider management options. Takata et al. [8.26] report that 3461 units of samples from agricultural fields were collected and analysed, and the data have been used to determine the Prefecture maximum permission level for agriculture of contamination level 2 (>5000 Bq/kg).

The Forestry Agency, under the organization of MAFF, has also developed a caesium deposition density map in litter and soil in forested areas affected by the Fukushima Daiichi accident (see Annex). This sampling programme was conducted five months after the accident and was based on the 4 km grid inside the 80 km radius and on the 10 km grid outside the 80 km radius. In each sampling unit, four samples were taken — north, south, east and west of a tree trunk. These sampling points had already been established for environmental standard points for biomass monitoring.

The Ministry of Environment is in charge of monitoring rivers and lakes. Starting on 30 August 2011, it began collecting soil samples from river beds and along lake shores. Initially, it was 193 units (envelope sampling design) from a 3 m × 3 m area using a 5 cm wide core sampler. The number of sampling units was then increased to 725, covering the entire area affected (see Fig. 8.28).

In addition to using the scraper sampling method (see Ref. [8.22]), there have been several other approaches to incremental soil sampling. Yamaguchi et al. [8.27] collected soil samples in paddy fields to estimate the depth distributions of ^{134}Cs, ^{137}Cs and ^{131}I. They used a core sampler, but paid attention to preventing cross-contamination of subsurface soils from the high radioactivity surface soil. Koarashi et al. [8.28] estimate the depth distribution in the soil from various land use types. They used a freeze core to avoid contamination, but in some land uses, some minor contamination from the upper part of the soil was found, especially in very low porosity forest soils.

8.2.7. Long term monitoring

After the emergency sampling, some soil sampling continued for more than three years after the Fukushima Daiichi accident for evaluating the vertical migration of ^{137}Cs in the soil column (see Annex). The data collected can be used to determine the change of external dose rates in the environment [8.29]. Matsuda et al. [8.30] conducted a long term survey of depth profiles of radioactive caesium in soils over a wide area surrounding the Fukushima Daiichi nuclear power plant. Using a scraper plate [8.30], “The soil was sampled at 5-mm intervals up to a depth of 20 mm, at 10-mm intervals between 20 and 50 mm, and at 30-mm intervals between a depth of 50 and 80 mm.” The soil sampling started

in December 2011, at 84 and 85 locations within a 100 km radius of the plant. Matsuda et al. [8.30] report the following downward migration:

— 12–22 December 2011 (81 sites) and 17–19 April 2012 (3 sites);
— 21 August to 26 September 2012 (85 sites);
— 26 November to 26 December 2012 (85 sites).

From the data, they observe marked downward migration rates V of 1.7–9.6 $kg \cdot m^{-2} \cdot a^{-1}$.

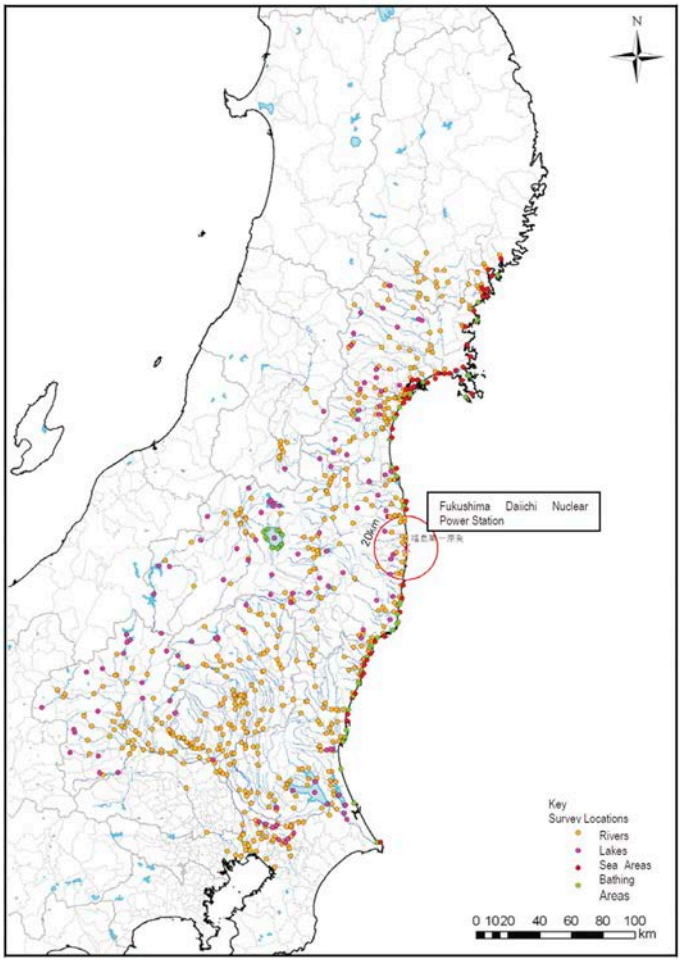


FIG. 8.28. Sampling site of the river bank and shore of lakes by Ministry of Environment, Japan.

Another long term survey of depth profiles of radioactive caesium in soils has been conducted by the Center for Research in Isotopes and Environmental Dynamics (CRiED), University of Tsukuba. Takahashi et al. [8.23] present data on the migration of caesium in various land uses (see Fig. 8.29). They collected soil samples in 5 mm increments for depths of 0–5 cm and in 1 cm increments for 5–10 cm. Roots were cut and collected with soil, and litter was collected separately. They also observed migration from the litter to soil in the first two years (see Fig. 8.30). Regular sampling of the riverbed and lake shore takes place 2–3 times a year.

FIG. 8.29. Location and sampling by CRiED.

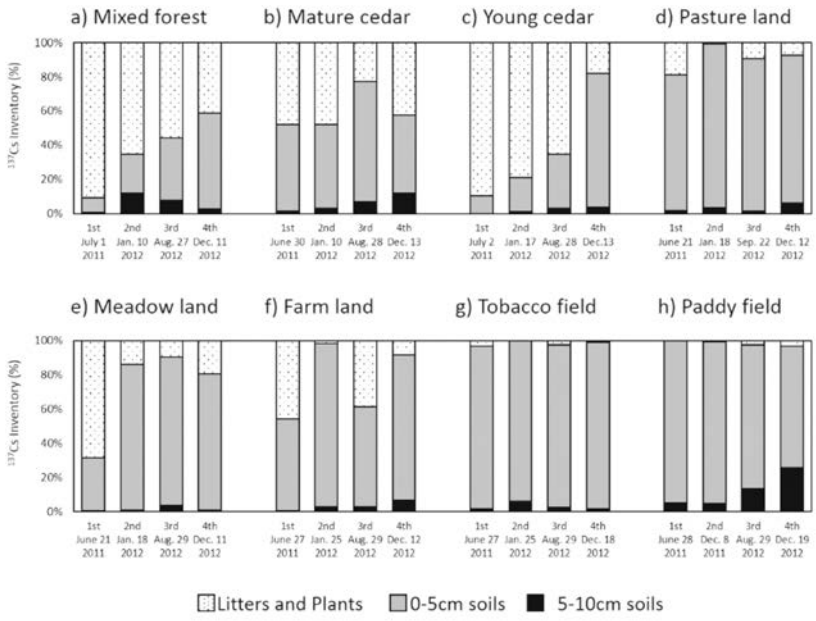


FIG. 8.30. Migration of ^{137}Cs during two years following the Fukushima Daiichi accident [8.23].

8.3. SAMPLING PROGRAMMES FOR COUNTRYWIDE MONITORING IN HUNGARY[1]

Nanba et al. [8.31] provide a detailed description about a Hungarian monitoring programme and present a study on an incident at the Paks nuclear power plant in 2003, the lessons learned in Hungary after the accident at the Fukushima Daiichi nuclear power plant and a countrywide monitoring programme proposal for Japan. Since each sample is unique, a sufficiently large number of units should be sampled to demonstrate their representativeness. In a consolidated period, sample variability dominates over the variability of the laboratory analysis — on the order of 20% compared with the analysis replication variation of just 1% or less.

The two major goals of the countrywide monitoring programme under the Ministry of Agriculture is to observe long term trends and to determine the ingestion dose from locally produced foodstuffs. The programme assesses the impact of all nuclear facilities in Hungary and at the borders, with emergency

[1] This section is based on Ref. [8.31].

response zones of 30 km, 80 km and 300 km around the facilities. Many circumstances are considered, such as geographical distribution of production, structural changes in agriculture and consumption habits, organization of public administration and capacities of radiochemical laboratories.

Essential parts of a countrywide monitoring programme include aerosol sampling with a large surface filter (>0.25 m^2) and sampled air volume (>40 000 m^3/week), continuous precipitation or fallout sampling, and soil sampling. Systematic soil sampling is applied when no extremities are expected; stratified random sampling is applied when the area has some specific characteristics to be taken into account (e.g. pond, river or well defined differences in the species); and the random method is applied when the environmental characteristics of the given area cannot be defined (e.g. forest with several types of tree). The goal of the sampling defines the method applied: the top soil layer is sampled to determine actinides and fresh fallout; in regularly cultivated agricultural land, the length of the core sample should be comparable with the depth of the ploughing; in undisturbed areas, Nanba et al. [8.31] recommend that core samples be collected. The support of the national geographical information system is essential.

In Hungary, food and feed samples are collected by the food and feed safety controllers and plant health officers of local authorities (19 counties plus the capital). From cereals, 60 samples are collected in a year, mainly wheat, reflecting its fraction of consumption and production. In vegetable sampling, the goal is to collect from open air production. Leafy vegetables (e.g. lettuce, spinach and sorrel) are good differential indicators, collected twice a year, three samples from three different locations. Potato and the root vegetables are collected in the harvesting period. The total annual number of samples is 330, including other types of vegetable. The annual sample number of fruits is 100 on the country level, with an emphasis on apples due to the high consumption rate and berries due to radioecological sensitivity.

Approximately 10% of the samples are freely chosen according to each county's specialties. However, the sample types are usually agreed at the beginning of the year but can change depending on circumstances. The collection of paired samples, such as leafy vegetable–soil, grass–soil and alfalfa–soil, is important to identify vulnerable areas: for example, one area had a sorrel–soil transfer factor seven times higher than average.

From seminatural and natural environments, samples are collected from moss, mushrooms and the meat of wild animals. Grass–soil pairs are often collected from undisturbed environments, and the transfer factor is calculated from the radionuclide content of the top layer of the soil and the grass. The inventory of a given radionuclide can be calculated from the fallout, and if one part of the grass sample is washed and the other not, the rate of the resuspension can

be determined as well. If the resuspension rate is not negligible, the radionuclide content of the washed grass has to be used to calculate the transfer factor.

On account of Hungary's size, there are no large differences in the environmental conditions, so the random sampling strategy is suited for many media. Nowadays, the concentration of anthropogenic radionuclides is low, therefore the sample amounts are rather high. Soil core samples are 10 cm in diameter, and 30–50 cm long cylinders are usually used for sampling.

The requirements when sampling include clearly marking the samples and supplying a sampling report together with the samples. In normal circumstances, the sampling team consist of only two people. In emergencies, however, a minimum of three people are required: the 'contaminated' person takes the samples; the second team member handles the tools and provides plastic bags to the 'contaminated' team member, avoiding any chance of cross-contamination; the third team member writes the sampling report, and marks and arranges the samples (in clean plastic bags or clean sample holders). Dose rate meters capable of measuring low doses and GPS are essential.

The features and behaviour of the individual radioisotopes has to be taken into account in each phase of the monitoring, starting from the planning and ending with the environmental model calculations and assessments. The case studies published in Nanba et al. [8.31] were fit for purpose for Hungary. Other countries and regions will have different needs and will require unique monitoring programmes defined by the climate, geographical circumstances, and social and economic conditions.

8.4. SAMPLING PROGRAMMES FOR COUNTRYWIDE MONITORING IN THE RUSSIAN FEDERATION

Currently in the Russian Federation, there is a ministerial style monitoring system. The State Atomic Energy Corporation "Rosatom" monitors the sources of radioactive emissions from nuclear facilities. The monitoring of the environment (i.e. atmosphere, water sources, soils and plants) is also carried out by the Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet), the monitoring of forest land is carried out by the Federal Agency for Forestry (Rosleskhoz) and the monitoring of farmland is carried out by the Ministry of Agriculture. Accordingly, the sampling programmes and techniques reflect the specific missions and tasks assigned to each ministry.

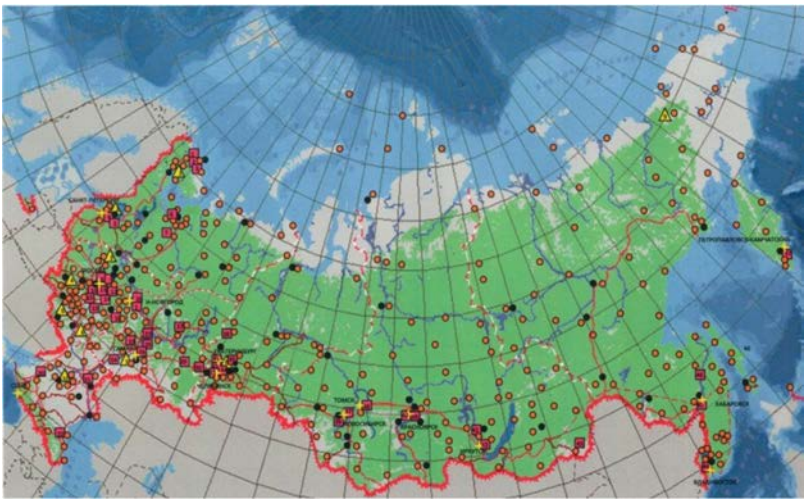
Monitoring is implemented at federal, regional and local levels. The monitoring network is organized on the basis of the administrative division of the country. The main, federal level, observation network is a system designed for the study of the environment of the country as a whole or large portions of its

regions. Additional networks are designed to address local problems of studying the environmental impact of radiologically hazardous facilities. The types of monitoring include the following:

— Planned original (background or initial) monitoring that fixes the contamination levels at the beginning of the monitoring programme;
— Planned (periodical or seasonal) monitoring performed in accordance with the monitoring programme;
— Unplanned (operational) monitoring carried out in accidental situations;
— Survey sampling conducted to identify the affected area.

8.4.1. Standing site selection

The specific challenges of a countrywide sampling programme in the Russian Federation is on account of the large area and the diversity of landscapes, soils and environmental conditions. The sites chosen for the monitoring network include the main natural landscapes (plains, flood and mountain) in mainstream phytocenoses (forest, grassland and wetland) and the major soil types in each of the different climatic zones (see Fig. 8.31).



Note: Black dots — sampling of radioactive aerosols using air filtration units; red dots — sampling of the radioactive fallout using tablets; triangles — nuclear power plants; squares — radiation hazardous facilities.

FIG. 8.31. Location of radiation hazardous facilities and points of radiation monitoring of Roshydromet.

The monitoring samples comprise air, water, sediments, soils and vegetation. The external dose rate and radionuclide concentrations (primarily ^{137}Cs and ^{90}Sr) are measured. Soil and grass are normally taken at the time of maximum development. It is assumed that the soil and vegetation samples are representative, and the sampling methods depend on the location, soil type and profile and the type of vegetation. External dose rate measurements are made at heights of 1 m and 2–4 cm above the ground prior to sampling.

8.4.2. Soil sampling

If the sampling site includes different relief elements (e.g. plateau, slope, slope lowering, saucer shaped ravines and temporal nulls), then soil samples from each relief element are collected. Soils are sampled in areas where the soil surface is undisturbed, using the envelope approach. Additional samples are collected where the external dose rate is twice as high. The samples are collected with a standard metallic ring 140 mm in diameter and 50 mm long (see Fig. 8.32) or with a special sampler (conductor).

The sampler has a sharp lower edge, and is high enough to accommodate the ring set position within and have an inside diameter that is no less than 3 mm lower than the outside diameter of the ring. During collection, the grass or other

FIG. 8.32. Ring samplers.

surface vegetation passes through the ring (or conductor) hammered into the soil, until the surface is parallel with the top edge.

The individual samples collected are combined in one composite sample of 1 kg. In areas covered by a root mat, the mass of the composite soil sample is at least 600 g. Soil samples are normally taken to a depth of 5 cm. However, in waterlogged areas or peatland, soil samples are taken to a depth of 20 cm. The sample is wrapped up tightly in paper or polyethylene film, put into a plastic bag and tied closed with string. When sampling with the conductor, the rings with soil are taken out from the conductor and packed in the standard way. Data on the radionuclide activities in the environmental samples are entered into a radiation monitoring database.

In forested areas, soil samples are taken with a sampler 40 mm in diameter and 15 cm long. A composite sample is prepared from 5–10 cores collected in an envelope pattern. Monitoring of the vertical distribution of radionuclides is carried out by sampling layers to a depth of 20 cm.

8.4.3. Vegetation sampling

Vegetation is used as an indicator of the impact of releases from radioactive sources. Vegetation sampling is conducted along with the soil sampling. Vegetation at the site cannot be dense, and the selection area depends on the yield. The plot is normally 1 m × 1 m; for higher yields, the plot size can decrease to 0.5 m × 0.5 m or 0.25 m × 0.25 m.

Plants are cut at a height that is not less than 3 cm above the ground. Individual samples are combined and mixed, from which a sample (≥1 kg) is taken for analysis. In low yields, the plot can be expanded to collect a 1 kg sample. The vegetation sample is wrapped in hard paper and labelled. The culture, vegetative stage and sampling area (for grass and cereal) or the number of the plants collected are recorded in the field notes.

8.4.4. Sampling programmes for forests

Figure 8.33 shows the regions covered by the forest sampling programme. When monitoring forests, Roshydromet collects litter, grass, mushrooms and berries. Rosleskhoz organizes a radiation monitoring network in forests in 17 regions covering 225 000 ha which were contaminated after the accident in the southern Urals and at the Chernobyl nuclear power plant. Radiation monitoring of soils and forest resources is carried out at 705 forest sites according to standard procedures. At each site, one composite soil sample is collected, and for each tree species composite samples of wood with bark, wood without bark and bark are collected. Methods for sampling trees are similar to those used in Section 8.1.5.

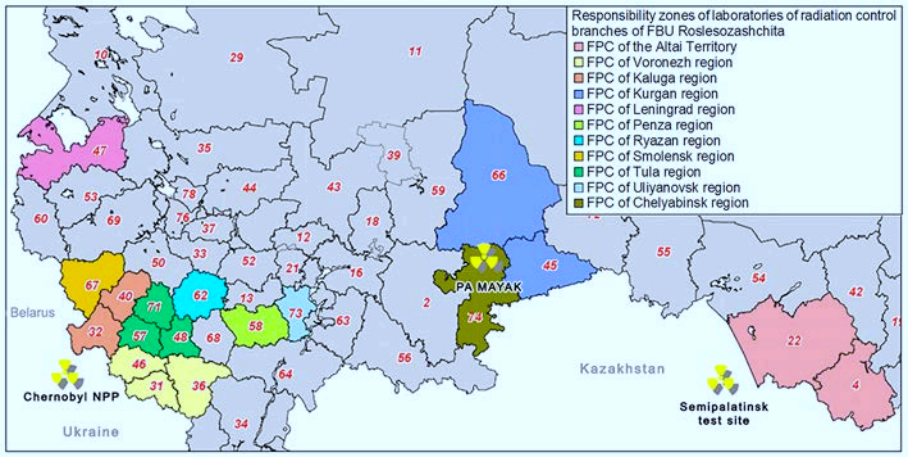


FIG. 8.33. Regions covered by the forest sampling programme.

Model trees are selected based on the mean diameter and height for each of the main tree species, and samples of wood, bark, small twigs, pine needles (leaves) and fruits (seeds) are collected (see Fig. 8.34).

Samples of mushrooms and berries are collected within a single quarter. Selected samples of mixed mushrooms are separated into three groups of high accumulation of radionuclides, an average gain and low accumulation, based on general information on radionuclide accumulation by different mushrooms species. The mixed sample consists of the most represented species of mosses, grasses and berries. Part of the grass cover, bushes and undergrowth are cut with a knife, shears or scissors at least 3 cm from the soil surface, and 8–10 samples are used for an averaged sample. The weight of the composite sample is at least 1 kg.

FIG. 8.34. Sampling wood in contaminated forest in the Bryansk region, Russian Federation.

8.4.5. Sampling programmes for farmland

The sampling strategy for farmland is similar to that used in Section 8.1.4. The agricultural monitoring network was created in the 1970s. In each region, there are around 20 monitoring sites. Altogether, this network includes more than 500 sampling sites. The sampling sites are located on typical farmland within the major soil types and in various natural and agricultural zones. After the accident at the Chernobyl nuclear power plant, the number of points was increased in the Bryansk, Kaluga, Oryol and Tula regions. The objectives of the sampling programme are:

— To identify changes in the radiation environment based on the dose rate and concentrations of ^{137}Cs and ^{90}Sr in the soil;
— To determine the parameters of accumulation of radionuclides (^{137}Cs and ^{90}Sr) in different vegetation species;
— To assess influence of soil properties on the parameters of radionuclide accumulation in plants;
— To evaluate the impact on the parameters agromeliorants on radionuclide accumulation in plants.

Samples are collected from the following:

— Arable soils;
— Agricultural plants;
— Water used for irrigation and animal drinking;
— Soils of grassland and hayfields;
— Plant stands of grassland and hayfields;
— Feed for agricultural animals.

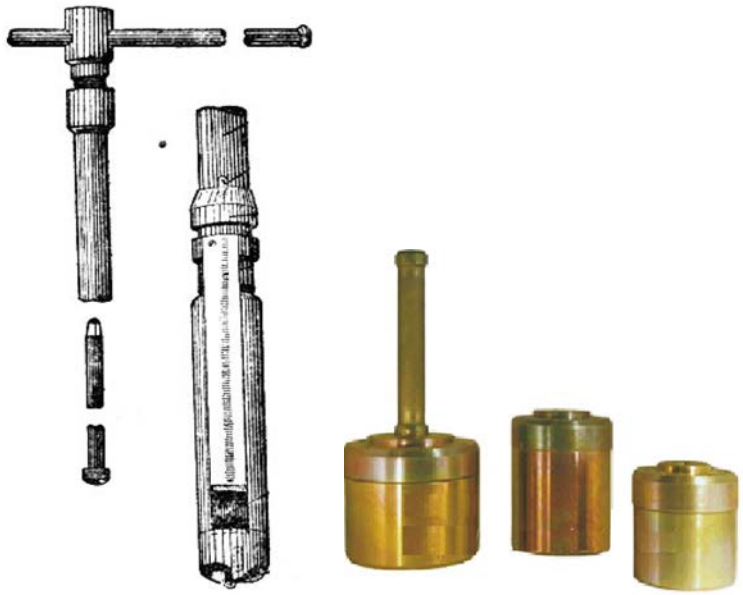
On the monitoring plots, soil samples are taken twice a year — at the beginning of the growing season and during harvesting. Vegetation samples are taken annually during harvesting. For fodder land, samples of the soil and vegetation used in feed are carried out no less than twice a year during the grazing and housing seasons at the animal checkpoints (stable period).

8.4.5.1. Soil sampling

At the point of sampling, the equivalent dose rate is also measured. The measurements of the equivalent dose rate are conducted at heights of 1 m and 2–4 cm above the ground. The average value is calculated and registered on the accompanying sheet with the sample records.

The size of the sampling area on arable land is no less than 1 ha, and the method used is route courses, which are laid in the middle of each sampling unit along its long side. If the test area is square, isolated samples should be selected from two diagonals or in one diagonal if the test area is rectangular. The selection of individual soil samples of arable land is carried out at a depth of the arable layer (typically ≥20 cm), before the spring field work and immediately after harvesting. Soil sampling is usually performed using a cylindrical corer 40–50 mm in diameter, such as a Malkov's modified corer (see Fig. 8.35). Various designs of samplers 8–10 cm in diameter and 10–20 cm long can also be used.

No fewer than ten individual soil samples are collected from each site. The soil samples are collected at equal distances on diagonals and in the centre of the site. Ten or more individual samples are collected within the sampling area and are combined to obtain a composite sample. From each sampling site, a 1 kg composite soil sample is created from the individual soil samples by the quartering method.



Malkov's modified drill Samplers for soil

FIG. 8.35. Equipment for soil sampling.

8.4.5.2. Pastures and grassland

Soil sampling from pastures and grassland is performed during the vegetation growth period. In tilled farmland, soil samples are collected from over a depth interval of 20 cm. If pastures or grassland have not been ploughed, the sampling depth interval is 10 cm. Sample collections are typically made twice a year (or more) during the grazing period and during the stabling season. The sampling areas from pastures or grassland are usually at least 1 ha. In natural grassland and pastures, where the majority of radionuclides are deposited in the upper 0–10 cm layer, sampling needs to be conducted over a depth interval of 10 cm. Various designs of samplers 8–10 cm in diameter and 10 cm long can also be used. Best practice is to make a single composite sample from ten or more individual samples of at least 1 kg. However, if there is a root mat, then a sample of at least 600 g is collected.

8.4.5.3. Vegetation sampling

Vegetation sampling of pasture and grassland is carried out during harvesting, whereas plants used for animal feed are sampled twice a year (or more): during the grazing period and during the stabling/housing season at the animal checkpoints. Individual vegetation sampling plots are typically 1 m × 1 m. The individual samples are combined to produce a composite plant sample (≥1 kg) of the homogenized mass. A composite sample normally consists of no fewer than five individual samples and may include either the whole plant or specific parts (stem, leaves, fruit, grain and root) if radionuclide concentrations are to be determined for the separate parts. The sample is wrapped in polyethylene or craft paper and labelled with the sample number, which is the same as the soil sample number, sampling date and location.

8.4.6. Sampling programme data[2]

Table 8.3 presents the concentrations of ^{137}Cs and ^{90}Sr in the soil according to type. Based on observations in 2011, the mean average concentration of ^{137}Cs and ^{90}Sr in soil was 13.4 Bq/kg and 5.1 Bq/kg, respectively. The accumulation of radionuclides in farm crops varies considerably for different climatic zones and is largely dependent on the soil properties. The highest availability of radionuclides is reported for peaty swamp, soddy podzolic sandy and sandy loam soil. Soils with higher fertility and heavier mechanical composition retain radionuclides more strongly. Grouping data on transfer factors according to soil–geography

[2] This section is based on Ref. [8.32].

TABLE 8.3. CONCENTRATIONS OF ^{137}Cs AND ^{90}Sr IN THE MAIN TYPES OF SOIL

	Soil type				Russian Federation (Far East)	Russian Federation (Whole)
	Chernozem	Soddy podzolic	Grey forest	Brown		
^{137}Cs						
No. sites	799	586	209	216	94	1902
Mean (Bq/kg)	18.5	9.2	13.8	9.8	7.3	13.4
SD	26	11.7	26	6.1	2.0	20
Range	<45	<21	<40	3.7–15.9	5.3–9.3	<34
^{90}Sr						
No. sites	680	543	196	179	72	1677
Mean (Bq/kg)	5.8	4.7	4.8	5.0	3.7	5.1
SD	5.2	3.6	4.8	2.8	2.3	4.4
Range	<11	1.1–8.3	<10	2.2–7.8	1.4–6.0	<10

Note: The data set does not include the territory contaminated as a result of the accidents at the Chernobyl nuclear power plant and Kyshtym. SD — standard deviation.

shows that transfer factors generally decrease from north to south because of the change from low fertility soils of light mechanical composition to heavier fertile soils. The radionuclide transfer factors to farm crops for these soils are one order of magnitude lower than for low fertility soils (see Table 8.4). The uptake of radionuclides by a crop is reported as the specific activity in a crop divided by the specific activity in the soil. Soil properties and crop characteristics are among the key factors influencing transfer factors for ^{137}Cs and ^{90}Sr.

The behaviour of ^{137}Cs is different from ^{90}Sr largely because of different mechanisms of radionuclide fixation in soil. The isotope ^{137}Cs exists in soil mainly in the non-exchangeable form, whereas an exchangeable type of sorption in soils characterizes ^{90}Sr. Maximum transfer factor values, both for ^{137}Cs and ^{90}Sr, are for sandy soil. There are high transfer factor values to vegetation from organic soils for ^{137}Cs and also large differences between transfer factors for ^{90}Sr and ^{137}Cs: 4.9 fold for cereals (grain), up to 67 fold for grain legumes (bean), around 30 fold for maize (grain) and more than 10 fold for maize (green mass).

TABLE 8.4. TRANSFER FACTOR VALUES OF ^{137}Cs AND ^{90}Sr

Crop	Soil group	N	Mean	Standard error	Min.	Max.
^{137}Cs						
Cereals	Clay	146	0.027	0.034	0.000 6	0.220
	Loam	230	0.043	0.069	0.002 1	0.886
	Sand	236	0.120	0.272	0.002 9	1.631
	Organic	39	0.044	0.035	0.004 0	0.195
Grain legumes (bean)	Clay	26	0.028	0.038	0.005 2	0.351
	Loam	107	0.039	0.079	0.005 4	0.210
	Sand	78	0.068	0.081	0.007 3	0.710
Maize (grain)	Clay	7	0.031	0.035	0.011 3	0.108
	Loam	11	0.038	0.028	0.008 2	0.032
	Sand	64	0.055	0.035	0.016 5	0.143
Maize (vegetative mass)	Clay	13	0.042	0.129	0.006 0	0.802
	Loam	11	0.049	0.017	0.012 0	0.054
	Sand	134	0.167	0.122	0.004 0	0.657
	Organic	3	0.141	0.032	0.104 0	0.160
^{90}Sr						
Cereals	Clay	74	0.233	0.431	0.017	1.66
	Loam	96	0.259	0.441	0.016	9.26
	Sand	156	0.358	0.346	0.004	2.70
	Organic	12	0.314	0.212	0.012	0.51
Grain legumes (bean)	Clay	30	1.594	2.615	0.150	36.7
	Loam	9	3.350	2.861	0.720	10.8
	Sand	18	4.117	7.864	0.934	35.0
Maize (grain)	Clay	27	0.797	0.455	0.130	6.60
	Loam	79	0.961	0.360	0.170	4.57
	Sand	62	1.653	0.661	0.300	8.50
Maize (vegetative mass)	Clay	8	1.231	1.249	0.180	2.64
	Loam	7	1.066	0.350	0.280	1.44
	Sand	24	1.363	0.459	0.120	2.77

8.5. SAMPLING PROGRAMMES FOR ENVIRONMENTAL MONITORING AROUND NUCLEAR POWER PLANTS IN THE RUSSIAN FEDERATION

8.5.1. Sampling points selection

The most important step in the development of a monitoring plan is the construction of the main elements of the plan, particularly the sampling system.

The major objective of the sampling plan is to evaluate the impact on the environment of the nuclear power plant in the context of obtaining the overall picture of its condition. Key features of the sampling plan are the sampling grid and the number of the sampling points and their locations within the plant control area. An obligatory condition for the sampling system design is to obtain a representative sample that also satisfies the necessary reliability requirements:

(a) Typical terrestrial ecosystems in the area need to be represented in the sampling plan.
(b) Sampling point locations need to ensure that samples are collected from typical components of the environment.
(c) The location of each sampling point should be representative of the widest monitoring area.
(d) The direction of the prevailing winds (wind rose) should be considered when selecting sampling points.
(e) Sampling points should reflect the contaminant distribution in the environment, formed from both natural processes and human activities.

In the case of a single source of radioactivity, the most appropriate sampling distribution plan is a radial–axial (or sector–segmental) scheme of sampling points based on a polar coordinates system with constant pitches by angular and radial coordinates. The required numbers of the sampling points for different atmospheric stability classes governing dispersion of radionuclides in the air are the following:

— A (maximum non-stable) requires no fewer than 15.
— B (non-stable) requires no fewer than 20.
— C (weakly stable) requires no fewer than 28.
— D (neutral) requires no fewer than 42.

The number of the points located along the outside the supervision zone is no fewer than eight, which is the number of directions of the wind rose. The grid nodes of the sampling grid have a constant spacing. In practice, however, sampling at these precise points is difficult to perform, since they may be located on roads or settlements. Special characteristics of the area (i.e. geology, climate, landscape, biology, hydrology and economy) being monitored needs to be taken into consideration. When designing the sampling grid, it is desirable to accommodate the necessary number of additional sampling points in these specific places. Therefore, the sampling grid usually looks as though the sampling points are distributed in a random way. The characteristic for sampling sites at the Smolensk nuclear power plant is given in Table 8.5.

TABLE 8.5. CHARACTERISTICS AND LOCATION CODE FOR SAMPLING PLOTS FOR SMOLENSK NUCLEAR POWER PLANT

No.	Coordinates		Plant association	Soil type
	Latitude	Longitude		
1	N 54° 14.303	E 033° 18.764	Firwood	Soddy sandy
2	N 54° 16.608	E 033° 11.601	Pinewood	Soddy podzolic sandy
3	N 54° 12.997	E 033° 11.801	Firwood with birch	Soddy podzolic loam
4	N 54° 14.720	E 033° 06.359	Dry meadow	Soddy podzolic sandy

8.5.2. Sampling programme

The state environmental radiation monitoring network includes observation points for radionuclides in the near surface atmosphere, fresh and marine waters, and stations and observation posts for the measurement of external gamma dose rate radiation. The location of radiation monitoring points in the 30 km zone around the Balakovo nuclear power plant is shown in Fig. 8.36. When conducting route surveys in areas of radiation hazardous facilities soils, water, sediments and vegetation are also sampled. The annual sampling includes the following:

— 22 points for external dose rate measurements;
— 7 points for sampling atmospheric aerosols, atmospheric fallout and snow;
— 4 sites for water sampling, bottom sediments and aquatic vegetation.

8.5.3. Geographic coordinates

Before soil sampling can begin the geographic coordinates of the corner points of every site has to be determined. The coordinate point of a sample is the centre of a circle with a 10 m radius within which the mixed soil sample will be collected, determined with a GPS receiver (latitude and longitude) (see Fig. 8.37).

8.5.4. Mobile laboratories

The mobile automated monitoring system has a portable scintillator connected to a radiometric scanning system. Usually ground based automated monitoring systems are operated with NaI scintillators. The mobile scanning requires optimization of speed and distance from the sources to the detector to achieve the prescribed sensitivity and the required cover area (see Fig. 8.38).

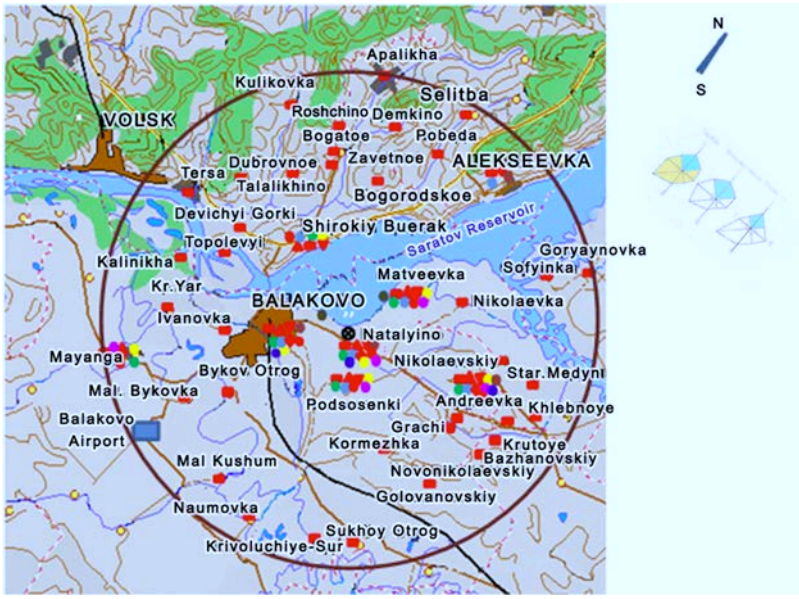


FIG. 8.36. Radiation monitoring sampling points in the 30 km zone around Balakovo nuclear power plant.

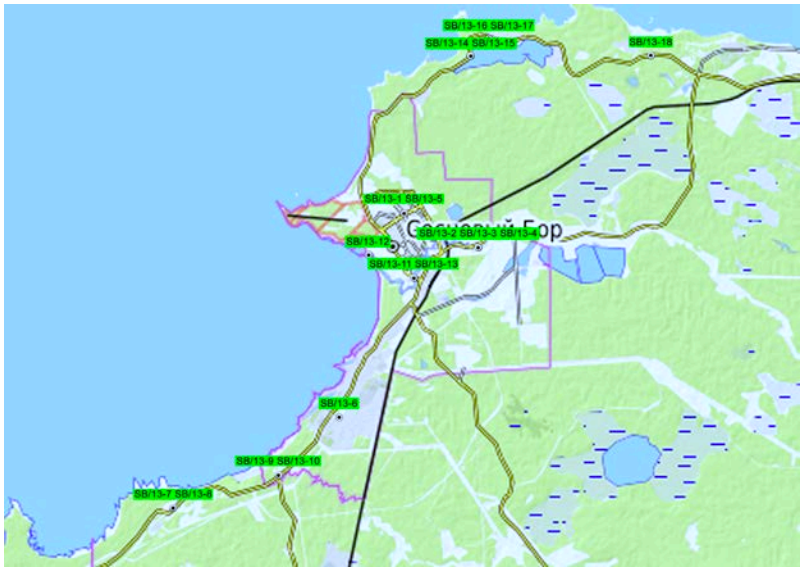


FIG. 8.37. Geographical reference of sampling points in the 30 km zone around Leningrad nuclear power plant.

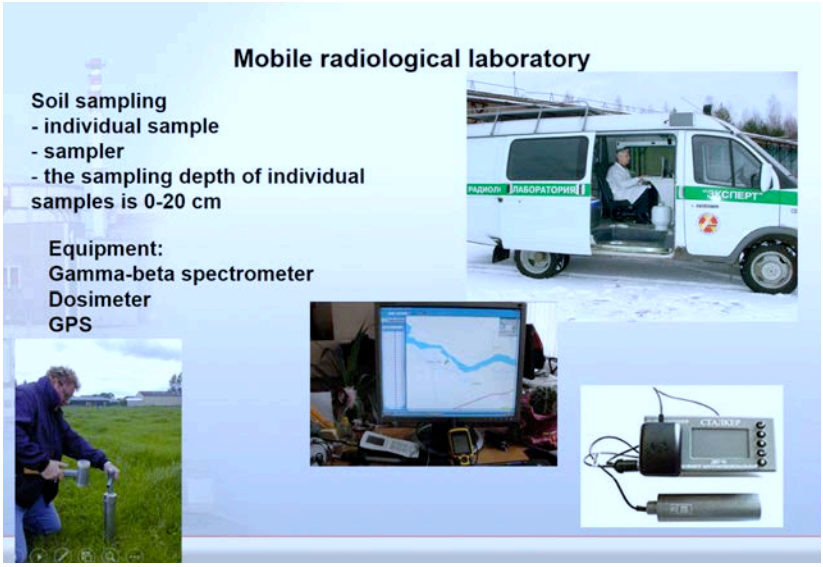


FIG. 8.38. Mobile radiological laboratory (Ministry of Agriculture, Moscow).

8.5.5. Soil sampling

Sampling areas around every nuclear power plant consist of 10 m × 10 m plots from meadow, arable land, flood plain and forest landscapes. Within the sampling area, five individual soil samples (0.5 kg) are obtained using the envelope method. On meadows and uncultivated land, individual soil samples are selected at a depth interval of 5 cm or 10 cm. In forests, samples of leaf fall and soil are taken at depth intervals of 10 cm. In waterlogged areas, soil samples are from a depth interval of at least 20 cm.

Five individual samples selected within the sampling area are combined to obtain a mixed sample. Roots, stones and other foreign material are removed. A 1 kg sample selected from the composite sample with the quartering method. This sampling plan yields monitoring data on the activity levels and the depth distribution of the soil contamination in the area of observation around the nuclear power plants. In all cases, the radionuclide concentrations in the soil in the observation zones of Russian nuclear power plants during normal operation corresponds to background levels (see Table 8.6). It was also found that the distribution of ^{137}Cs in the 15 km and 30 km zones around the Kursk nuclear power plant has a log-normal character (see Fig. 8.39). The information was used for assessments of the current doses to the public in the settlements surrounding the power plant.

TABLE 8.6. ^{137}Cs CONTAMINATION DENSITY IN SOILS AROUND NUCLEAR POWER PLANTS (kBq/m^2)

Nuclear power plant	Observation zone	Regional background level
Balakovo	0.44 ± 0.12	0.45 ± 0.16
Beloyarsk	13 ± 3	12 ± 5
Rostov	1.5 ± 0.4	1.5 ± 0.3
Kalinin	0.53 ± 0.07	0.32 ± 0.14
Kol'skaya	0.23 ± 0.08	0.22 ± 0.06
Kursk	3.7 ± 0.8	4.9 ± 1.9
Leningrad	1.9 ± 0.2	1.7 ± 0.2
Novovoronesh	6.0 ± 1.5	5.2 ± 1.9
Smolensk	4.4 ± 1.7	3.5 ± 2.6

8.5.6. Soil sampling for farmland

8.5.6.1. Arable land

The sampling area on arable land is at least 1 ha at depth intervals of typically no less than 20 cm. The soil samples (≥10) are selected before spring work in the fields and immediately after harvesting, and are collected at equal distances on diagonals and in the centre of the site. Soil samples are generally taken using a cylindrical corer 40–50 mm in diameter (e.g. Malkov's modified drill). Various sampler designs 8–10 cm in diameter and 10–20 cm long are also used. Ten or more individual samples are combined and mixed to obtain a bulk, composite sample by the quartering method.

8.5.6.2. Pasture and grassland

The sampling areas on pasture or grassland are typically at least 1 ha. Sampling is conducted during the vegetation growth period at a depth of at least 20 cm in arable fields but 10 cm in unploughed soil. Sample collections are carried out twice a year (or more): during the grazing period and during the housing season of the animals. A single, composite integrated sample (≥1 kg). If there is a root mat, the composite sample should be no less than 600 g.

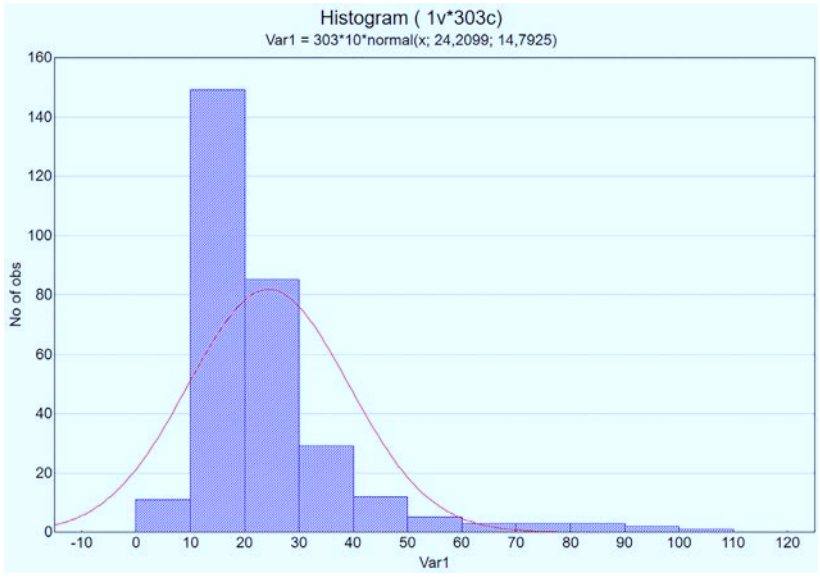


FIG. 8.39. Distribution of ^{137}Cs in the 30 km (top) and 15 km (bottom) zone around the Kursk nuclear power plant (Bq/kg).

8.5.7. Radionuclide distribution in the soil profile

The vertical redistribution of radionuclides in the soil profile is an important factor affecting the uptake and accumulation of radionuclides in plants, as well as the surface exposure dose rate. The method of soil sampling depends on the landscape (arable land, meadow, flood plain or forest) and the objectives of the study. Special samplers can be used to assess the vertical radionuclide distribution in the soil.

The method of monoliths and the method of soil sections or different samplers are normally used to collect samples to study vertical migration in the soil profile. The soil monolith sampling procedure is the same as for the soil horizon sampling procedure, but the depth of the samples differs. The first soil sample is taken from the upper layers and subsequent samples are collected by gradually moving to the lower layers. As a rule, the sampling depths are 0–2, 2–5, 5–10, 10–20 and 20–30 cm.

A soil pit is first dug and the soil horizons are measured and recorded. The depth is typically 1.5 m, and the soil horizons are marked on the side wall (see Fig. 8.40). One soil sample is selected from each horizon, starting from the lower horizon and gradually moving up. Mat and litter are selected separately.

The method of monoliths is also often used to determine concentrations of radionuclides in different soil horizons (see Fig. 8.41). A monolith of 0.2 m × 0.2 m (or 0.3 m × 0.3 m) is made, with the first soil sample taken from the upper horizons and gradually moving down. Different samplers or a shovel are used to collect a vertical profile of soil samples for determining the radionuclide distribution in the soil layers on arable land. Although the sampling procedure is the same, the depths differ and do not depend on the depth of the soil horizons (generally 0–20, 20–30, 30–40 cm and deeper). The first soil sample is collected from the upper layers then gradually moving down.

8.5.8. Vegetation sampling

8.5.8.1. Forest

Control plots in forests are used to determine parameters such as species composition, tree characteristics, understory species composition, biomass and percentage of dead tree crops. Description of the vegetation is made during the period of maximum growth of the major species. Tree species are not sampled at routine monitoring sites. Forest litter, which can be an indicator of intake of radioactive fallout is sampled at specially selected sites. Grass samples are collected at the same time as soil samples. The sampling area depends on the yield (normally 1 m^2). The ground part of the grass cover, bushes and undergrowth are

FIG. 8.40. Soil horizons study. (Courtesy of V. Anissimov, Russian Institute of Radiology and Agroecology, Obninsk.)

FIG. 8.41. Study using the monolith method. (Courtesy of V. Kiznetsov, Russian Institute of Radiology and Agroecology, Obninsk.)

cut with a knife, shears or scissors (≥3 cm above soil surface). The composite sample (1 kg) includes the most representative species of mosses, grasses and berries. Samples of mushrooms and berries are selected within a single highlight or quarter where the control site is located. Selected samples of mushrooms are separated into three groups of high accumulation of radionuclides, an average gain and low accumulation.

8.5.8.2. Meadow and crops

Vegetation samples are taken annually during harvesting and are selected at the same time as soil samples are collected. The sampling area varies (0.25–2 m^2) depending on the yield and can be expanded. Plant sampling is the same as for forests.

Crop samples are combined, mixed and a composite plant sample (≥1–2 kg) is taken from the obtained homogenized mass (≥10 individual samples) and may include either the whole plant or specific parts (stem, leaves, fruit, grain and root) if radionuclide concentrations are to be determined for the separate parts. The sample is wrapped in polyethylene or craft paper and labelled with the sample number, which is the same as the soil sample number, sampling date and location (see Table 8.7).

TABLE 8.7. TYPICAL SAMPLING PROGRAMME

Land use	Sample	Periodicity of sampling
Arable area	Soil	Before planting During harvesting
	Vegetable, fruit, potato, grain	During harvesting
Natural grassland	Soil, grass	Before grazing of farm animals Cutting the first grass mowing and during the first grazing Cutting the second grass mowing and during the second grazing

Note: Required indicators are ^{137}Cs, ^{90}Sr and external dose rate.

8.5.8.3. Sampling data

The monitoring data on soil and plant radionuclide activities are used to describe the dynamics of accumulation of radionuclides in different plants. These data can be also used for the calculation of internal dose due to consumption of local foods, as well as for model parameterization and prediction of the impacts fallout from nuclear power plants, including from accidents. Figure 8.42 presents soil to plant transfer coefficients for ^{137}Cs and ^{90}Sr for grains and grasses. Comparative analysis of the long term data on radionuclide transfer to plants has shown high variability of radionuclide concentrations in plants, which can be explained by the site variations in soil properties, weather conditions and different farming techniques. There is a 1.7–5.3 fold difference in the accumulation of ^{137}Cs and ^{90}Sr in 2000–2009. The data were used to determine an annual intake of the radionuclides by the population living in the vicinity of the power plant of 180 Bq and 130 Bq for ^{137}Cs and ^{90}Sr, respectively. This is almost two orders of magnitude below the limit of annual intake set by the radiation protection regulation. The main contributors of ^{137}Cs to the diet of population were milk (27.7%), potatoes (22.8%) and meat (17.1%) and for ^{90}Sr crops and milk (15.8%). The resulting expected effective dose of internal exposure in the settlements near the Rostov nuclear power plant was thus 13 μSv.

8.6. SAMPLING PROGRAMME FOR ENVIRONMENTAL MONITORING IN THE UNITED KINGDOM

In the United Kingdom, all environmental monitoring programmes are undertaken by the Environment Agency, the Scottish Environment Protection Agency (SEPA), the Northern Ireland Environment Agency (NIEA) and Natural Resources Wales. The Food Standards Agency (FSA), Food Standards Scotland (FSS) and SEPA work closely together and are responsible for monitoring foodstuffs, including crops. They are responsible for the protection of the environment and waste disposal under the Environmental Permitting (England and Wales) Regulations 2016 and the Radioactive Substances Act 1993 for Scotland and Northern Ireland; they are responsible for food safety throughout the United Kingdom under the Food Standards Act 1999. Legislative measures for the protection of wildlife are implemented through Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (EU Water Framework Directive) [8.33] and Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora (EU Habitats Directive) [8.34].

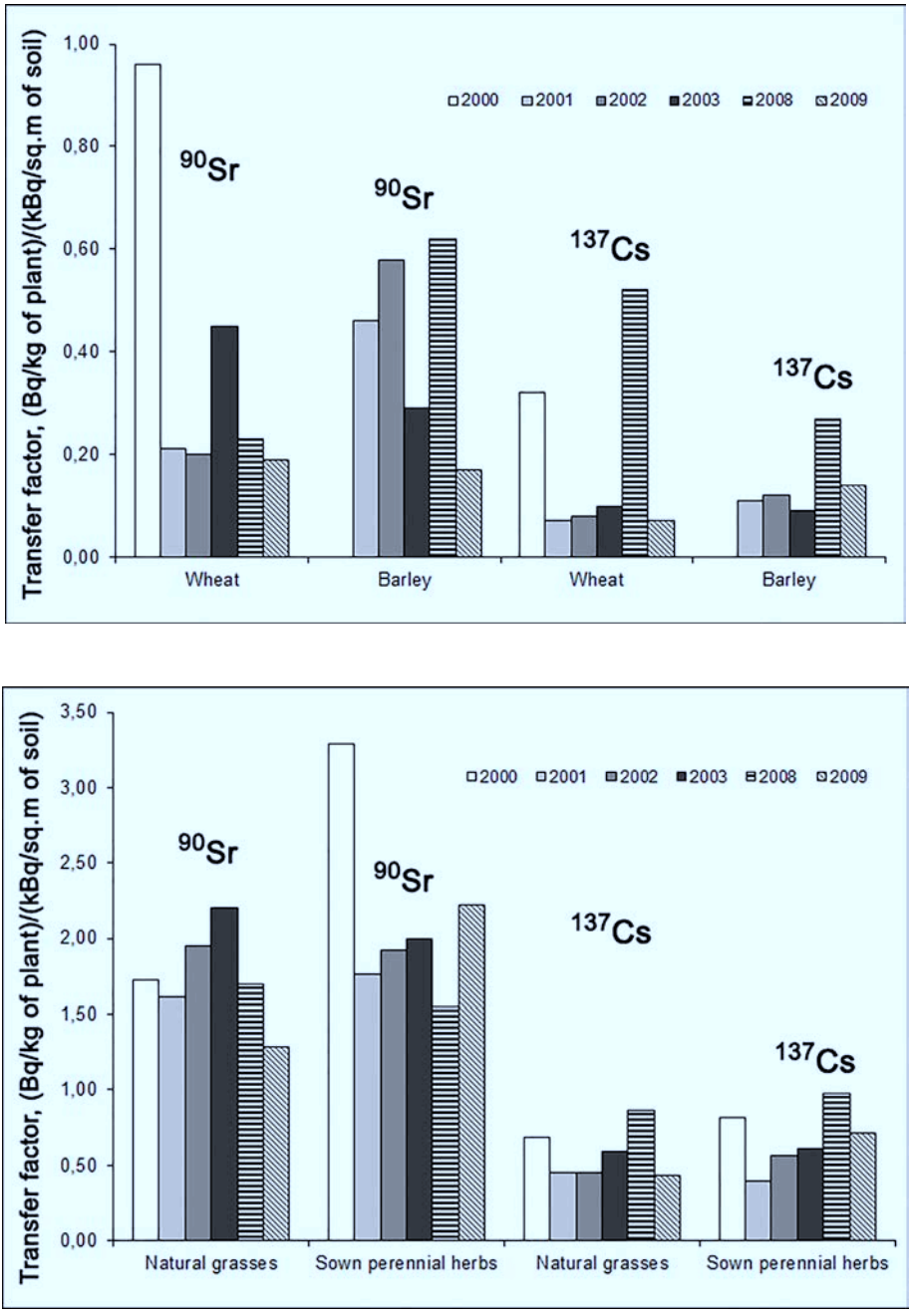


FIG. 8.42. Transfer coefficients of ^{90}Sr and ^{137}Cs in grain cereal crops (top) and grasses (bottom), Rostov nuclear power plant.

The monitoring programme is undertaken by the environment agencies, in parallel with site operators, and in support of their regulatory roles under the law and serves several purposes, including:

— The establishment of long term trends in close proximity and distal to nuclear sites;
— The assessment of dispersion of radionuclides in the environment;
— The evaluation of doses to the public from food stuffs;
— The assessment of contamination in affected areas following the accident at the Chernobyl nuclear power plant;
— The monitoring of imported foodstuffs from Japan to confirm the Japanese safeguards are working [8.35].

8.6.1. Review of sampling and monitoring programmes

The Environment Agency commissioned a review of sampling and monitoring programmes and published the results in 2007 [8.36]:

> "The aim of this project was to identify, and provide guidance on, best practice techniques for these monitoring programmes. These techniques encompass the instrumental monitoring of contamination and dose rates as well as the collection and preparation of food, indicator and air/deposition samples. ...
>
> "The work carried out for this study included:
>
> - reviewing the literature on guidance and standards on sample collection protocols and radiological monitoring of the environment;
> - identifying best practice techniques for individual environmental media and monitoring tasks;
> - preparing guidance notes to implement these techniques."

The review included a cost–benefit analysis of different techniques and best practices for environmental monitoring and sampling including for vegetation and soil sampling.

8.6.2. Guidance on planning and implementing monitoring surveys

In 2010, SEPA, FSA and the Environment Agency jointly published Radiological Monitoring Technical Guidance Note 2 [8.37] to provide guidance on planning and implementing radiological monitoring surveys. It builds in part

on the 2007 review [8.36] and makes clear recommendations on radiological monitoring, including the sampling of soils and vegetation. Guidance Note 2 [8.37] describes the need to define clearly the objectives of the monitoring programme and provides eleven such examples:

(a) Assess total representative person dose;
(b) Assess dose as an operator's performance measure;
(c) Assess total impact on wildlife;
(d) Assess impact on wildlife as an operator's performance measure;
(e) Provide public and stakeholder reassurance;
(f) Check complementary monitoring;
(g) Assess background (very far field);
(h) Assess long term trends;
(i) Comply with international obligations;
(j) Detect abnormal, fugitive and unauthorized releases;
(k) Understand or monitor radionuclide behaviour in the environment.

Guidance Note 2 [8.37] recommends that the monitoring programmes be designed to meet the following generic principles:

(1) Health and safety: Benefits should be balanced against risk.
(2) Benefits exceeding impacts: Benefits should exceed any significant environmental detriment.
(3) Satisfy international requirements: Programmes should satisfy international requirements (e.g. IAEA safety standards).
(4) Objective based: Monitoring should be clearly linked to well defined objectives.
(5) Proportionate: The design and management of programmes should be proportionate to past, current and future potential impact, taking account of how dynamic the environment is. It will generally be proportionate to have a larger environmental monitoring programme where the dose from discharges to air or water exceeds 0.02 mSv/a to ensure that a realistic dose assessment can be performed.
(6) Complementary: Programmes should avoid unnecessary duplication.
(7) Satisfy stakeholder concerns: Programmes consider stakeholder concerns as far as reasonably practical.
(8) Based on authorizations: Selection of specific radionuclides should be based on the source term (taking account of the impact) and limited by legal permits/authorizations.
(9) Optimized: Programmes should be optimized to achieve the maximum number of objectives from a minimum number of samples.

(10) Meet quality standards: Programmes should be undertaken to defined quality standards equivalent to the relevant ISO standards [8.38–8.40].
(11) Appropriate performance criteria: Performance criteria should include uncertainty criteria, limit of detection and analytical turnaround. Performance criteria will be linked to objectives and the urgency and importance of the data.

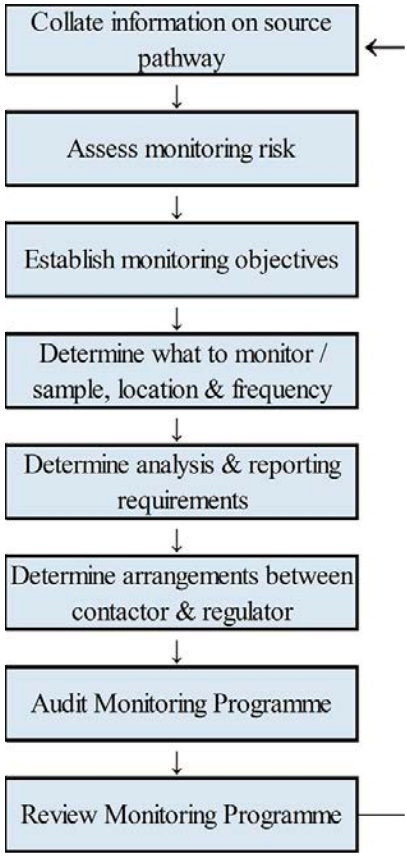
Figure 8.43 summarizes the design process for an environmental monitoring and sampling programme Guidance Note 2 [8.37] recommends. Information on the source pathway should include a conceptual model developed from as much information about the source, site boundaries, site characteristics including soil, hydrology, climate and meteorological conditions, site history, habit survey information, models of dispersion and existing spatial, temporal monitoring data [8.37]. According to Guidance Note 2 [8.37], the impact of the site is also assessed and programmes for lower impact sites (<0.02 mSv/a) are treated separately from higher impact sites (>0.02 mSv/a) and effort invested is allocated proportionately. For sites with the lowest impact (<0.001 mSv/a), "no programme will be required" [8.37]

Guidance Note 2 [8.37] recommends the relevant monitoring objectives (a)–(k) be established for the monitoring programme and will also reflect who is undertaking the work, its scope and site impact. It also provides recommendations on the appropriate frequency of monitoring and best practices for monitoring and sample collection (see table 4 of Ref. [8.37] for guidance on grass, herbage and soil sampling). Additional guidance includes examples of the detailed considerations for the analytical requirements of a monitoring programme and the review of the execution and outputs of the programme: (i) quality assurance requirements; (ii) health, safety and the environment; and (iii) reporting, records, assessment and interpretation [8.37].

8.6.3. UK Soil and Herbage Pollutant Survey[3]

The UK Soil and Herbage Pollutant Survey (UKSHS) was undertaken in 2001 and 2002, and the "primary objective was to establish a baseline for pollutant levels in soil and herbage in the UK" [8.41]. The research project was jointly sponsored by: (i) Environment Agency; (ii) Department for Environment, Food and Rural Affairs; (iii) National Assembly of Wales; (iv) FSA and FSS; (v) SEPA; (vi) Environment and Heritage Service (Northern Ireland); and (vii) Scotland and Northern Ireland Forum for Environmental Research. The three main types of site included in the UKSHS were rural, urban and industrial

[3] This section is based on Ref. [8.41].



Source: Figure 1 of Ref. [8.37].

FIG. 8.43. Process of designing and implementing environmental radiological monitoring programmes.

sites [8.41]: "Although the site types are different, the general procedure used to select a suitable site and location to sample was a generic one" and "there was a tiered approach to the selection of sampling sites. Information collated, decisions made and the reasons for those decisions were documented to produce an auditable series of justifications for the selection of each site and sample location." The selection process included the following:

(a) The approximate grid reference for each rural site was determined from the intersection of a systematic 50 km sampling grid across the United Kingdom. For industrial sites, the environment agencies provided grid references and names of locations to be sampled.

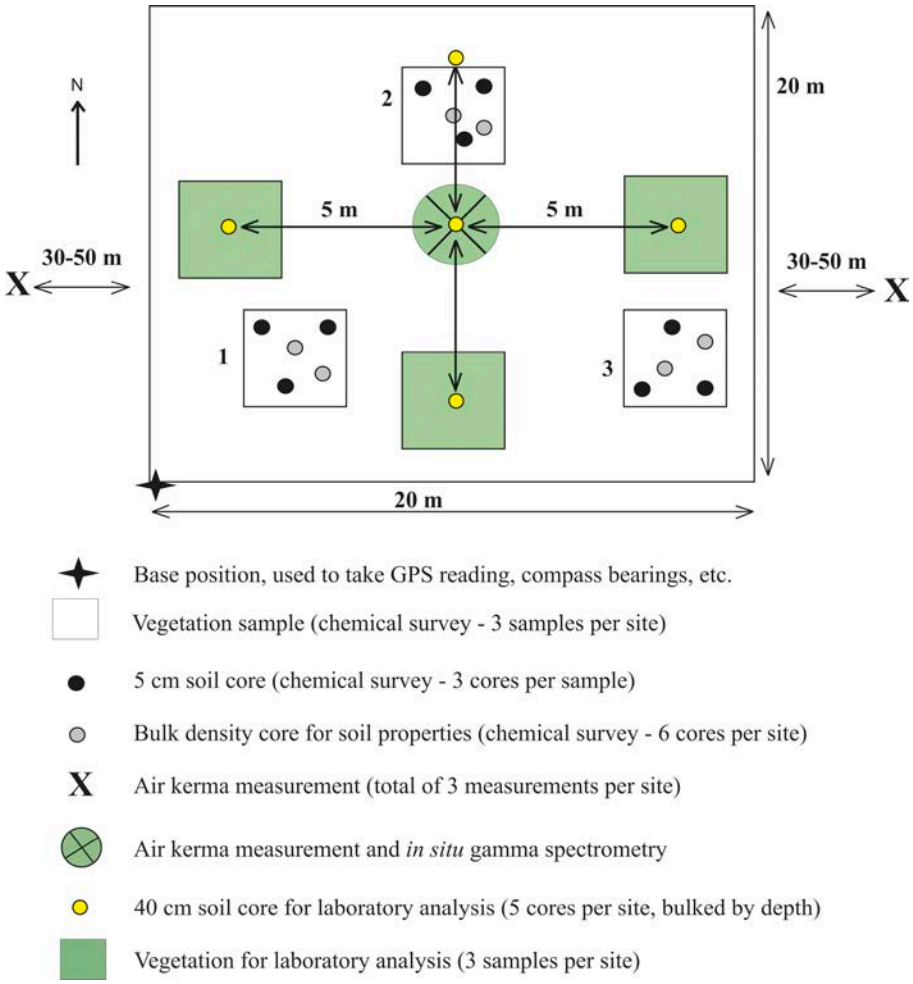
(b) A desk based review of each sampling location was undertaken and landowners were contacted and interviewed using a structured questionnaire to review the suitability of each candidate site, including:
— Presence of undisturbed land;
— Presence and type of vegetation;
— Site history.
(c) Once permission had been given, a site information pack was prepared for the sampling team (see the appendices to Ref. [8.41]).
(d) On-site, the field team visited each site based on the information contained within the site information packs, undertaking a visual assessment to confirm that the site met the suitability requirements.

Sites had to be within 1 km of the 50 km × 50 km grid intersection point for rural sites and within 500 m off the grid reference for the urban sites (common land, parks and public gardens) and industrial sites (sampled at three locations within a 60° angular sector downwind of the prevailing wind direction and one site upwind, avoiding woodland). This approach provided some flexibility in identifying an undisturbed site. At each sampling location, the following information was recorded:

— Unique site identification code;
— Grid reference from a differential GPS;
— Sampling team personnel;
— Date, time and weather conditions;
— Description of site and land use;
— Proximity of site to industry and its direction;
— Site history;
— Any additional relevant freeform notes (supplemented with a digital photograph).

A total of 128 rural sampling sites were visited. Each sampling site was selected to reflect the local vegetation diversity and was used to measure gamma ray air kerma rates and in situ gamma spectrometry. Figure 8.44 shows the sampling scheme for all determinants in the survey. Soil samples for chemical analysis were collected using an Eijkelkamp coring kit (53 mm in diameter and 50 mm deep). Each sampling site was at least 20 m from trees, walls or buildings.

For the radiometric analysis, soils were cored to a depth of 400 mm with a 105 mm in diameter golf hole corer. Although heavily dependent on soil bulk density, the gamma photon contribution to dose rate below 700 keV is negligible below 400 mm.



Source: Figure 3.2 of Ref. [8.41].

FIG. 8.44. Sampling plan for rural and urban sites, covering an area of 20 m × 20 m.

Prior to coring overlying vegetation was cut and leaf litter/stones were removed by gently scraping the surface with a knife to expose the surface of the soil. Five cores were extracted from the end points and the centre of an X (each arm 5 m) after the air kerma and in situ measurements were made. Where stones presented difficulties in penetrating the soil, the corer was offset and another core attempted. Failure following three attempts usually resulted in a shorter core being extracted. The corer was wiped with a paper towel between cores for a given site. Each core was subdivided into 0–50 mm, 50–100 mm, 100–150 mm,

150–200 mm, 200–300 mm and 300–400 mm with a knife. The knife was also wiped between sections to avoid cross-contamination. Each core slice was then combined and pooled for each depth interval. At 11 of the 128 sites, calibrations sites for the in situ gamma spectrometer were designated in areas of contrasting soil, geology, topography and depositional setting. In addition to providing data for the calibration of in situ detectors, the ^{137}Cs vertical activity distribution could also be calculated. At the calibration sites, each core slice was treated individually so that the heterogeneity in spatial and depth distributions could be characterized. The samples were double-bagged in plastic bags, labelled with the unique sample and project identification, date of sampling and initials of person sampling and placed in cool boxes for transport back to the laboratory.

Vegetation samples were collected after the in situ gamma spectrometry and air kerma measurements were acquired. Vegetation was sampled with sheers with stainless steel blades and bagged similarly to the soil. Wood et al. [8.41] report:

> "Three vegetation samples were collected from each rural and urban site. Each industrial site had four or more sampling points and one vegetation sample was taken from each one.
>
> "Before sample collection and in order to 'clean' the shears, they were used to randomly cut vegetation outside the 20 m × 20 m area. The shears were wiped clean with tissue between sample collections. The 20 m × 20 m area was surveyed for vegetation coverage and species diversity. Using a quadrat (size 0.25 m × 0.25 m) to ensure that the area of vegetation sampled could be accurately recorded, three vegetation samples were collected in an inverted V shape (see [Fig. 8.44]). Vegetation within the quadrat was clipped to 10–20 mm above the soil surface, avoiding worm casts and surface litter.
>
> .....
>
> "All samples collected from one particular site location were stored in a site-designated cool box, along with ice packs to prevent sample deterioration during transit, and the boxes sealed with tape for transfer to the UoL [University of Liverpool] laboratory.
>
> "On arrival at the UoL laboratory, samples were logged using the UoL sample tracking system and the integrity of the samples checked.
>
> "The chemical survey samples were stored as follows:

- soil samples in a refrigerator/cold room at <4°C;
- vegetation samples placed into a freezer at <20°C.”

An example of the results derived from the UKSHS is illustrated in Fig. 8.45, which presents the in situ gamma spectrometry derived dose rate estimates and apportions gamma dose rate to natural sources and ^{137}Cs.

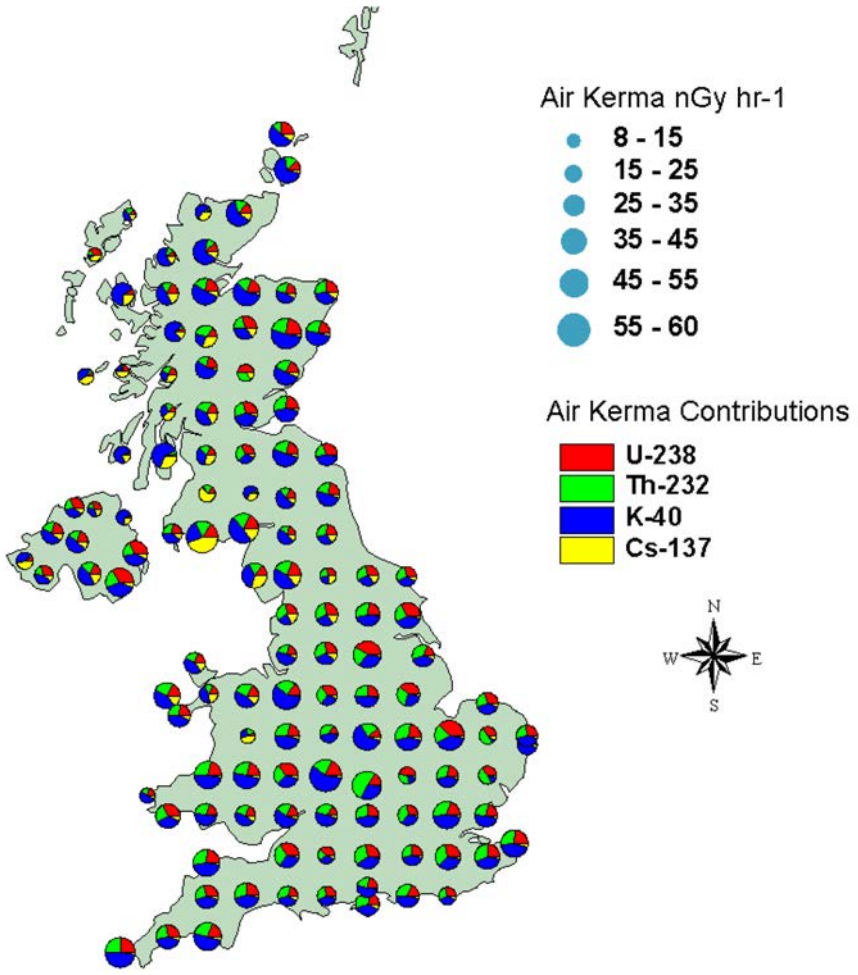


FIG. 8.45. Example of output from the UKSHS estimates of air kerma and attribution of natural and anthropogenic sources to the gamma dose rate estimates.

8.6.4. Example of a UK legacy site: Dalgety Bay

In a 2012 report[4] to the Scottish Government, the Committee on Medical Aspects of Radiation in the Environment (COMARE) states:

> "The first ^{226}Ra contaminated particle was discovered and recovered from the foreshore at Dalgety Bay in 1990 as part of the baseline monitoring campaign by Babcock Engineering Services for the Rosyth Naval Base. Once it was identified as ^{226}Ra, its origin was attributed to the historical operations on the Donibristle airfield. The then National Radiological Protection Board (NRPB)...undertook two surveys of the Bay in 1990 and 1991 and recovered 220 particles and 354 objects."

Tyler et al. [8.42] report that since their initial discovery, further monitoring campaigns undertaken by contractors operating on behalf of the Ministry of Defence and SEPA have recovered many hundreds of particles from foreshore areas. The hazard and risk posed by these ^{226}Ra contaminated materials and artefacts continues to be the focus for a number of investigations, including the dose received by accidental ingestion. The research and site investigations that have been undertaken have been summarized and compiled to assess the site history, condition and risk to the public and include the SEPA Dalgety Bay Appropriate Person Report [8.43] and the 15th Report of COMARE [8.44].

With the lack of documented evidence of on-site activities, historical evidence was gained from eyewitness accounts by interviewing people who had lived in the area or worked on the airfield during its wartime and post-war operations [8.43]. Further evidence was extracted from aerial photography, which was also useful in corroborating eyewitness accounts [8.45]. A 1949 aerial photograph shows a conical shaped area (termed 'tip'). A series of aerial photographs after 1949 show systematic erosion to the tip and subsequent movement of material to the foreshore areas to the north east. This tip has since been demonstrated to contain ^{226}Ra contaminated material and artefacts. Understanding the dynamic behaviour of this coastal environment and its evolution has been important in developing a conceptual site model for the occurrence of contaminated ^{226}Ra particles, dials and other artefacts on the foreshore areas [8.43, 8.44]. This interpretation has also been important in understanding the possible location of ^{226}Ra contaminated material within the headland and elsewhere on-site.

The Ministry of Defence sold the site in three separate parts during the early to mid 1960s. In the 1970s, a sailing club was established with the main

[4] See www2.gov.scot/resource/0041/00412964.pdf

clubhouse built across the margins of the tip area. Material excavated for the foundations was kept on-site and used as a mound to help to level the site. The site has a very attractive aspect overlooking the Forth Estuary, which has resulted in an increase in occupancy of the site by both sailing club members and the public, including dog walkers. Given the complexity of the site, only an example of the approach adopted is summarized here and focuses on an investigation of part of the site known as the headland. The objectives of the investigation were:

(a) To assess and confirm the presence of ^{226}Ra contaminated materials on and within the site;
(b) To recover contaminated material from the surface of the site;
(c) To establish that there were possible pathways for ^{226}Ra contaminated material to leave the headland.

A staged approach to the site investigation was therefore adopted to gather intelligence on the site prior to any intrusive investigation. First an interpretation of the vertical and spatial structure was needed. This was gained from a series of ground penetrating radar (GPR) transects across the site. The GPR data were used to delineate the depth of the made ground to bedrock, identifying geological and morphological features that could provide information on the construction and infill structure of waste materials. Importantly, as the site was thought to have been used as a bombing test range during the Second World War, the GPR survey was also used to identify any artefacts that might have indicated the presence of unexploded ordinance. This information was also needed to satisfy the risk assessment required before any work could be undertaken to dig into the site. The 2–3 m depth to the unconsolidated infill meant that a 100 MHz and 200 MHz unshielded GPR system was most successful in identifying the structure of the site. Figure 8.46 provides an example of the data provided by the GPR surveys, showing structures that may reflect the sequential tipping of the waste into the headland area. Mobile gamma spectrometry surveys were also used on several occasions (see Fig. 8.47) and an example of the survey data is presented in Fig. 8.48. Surface excavation was undertaken where isolated hot spots of surface contamination were identified (see Fig. 8.49).

Hand held detectors were used to assess on-site bulk soil samples to identify the presence of ^{226}Ra contaminated artefacts, material (ash) or soil. The excavated area was also checked to assess whether the contamination was still present within the area of excavation. Once the ^{226}Ra contaminated material had been identified and isolated, a sample was taken, bagged and logged, and the material removed from the site for storage and disposal. The surface of the site was protected from further contamination with plastic sheeting (see Fig. 8.49).

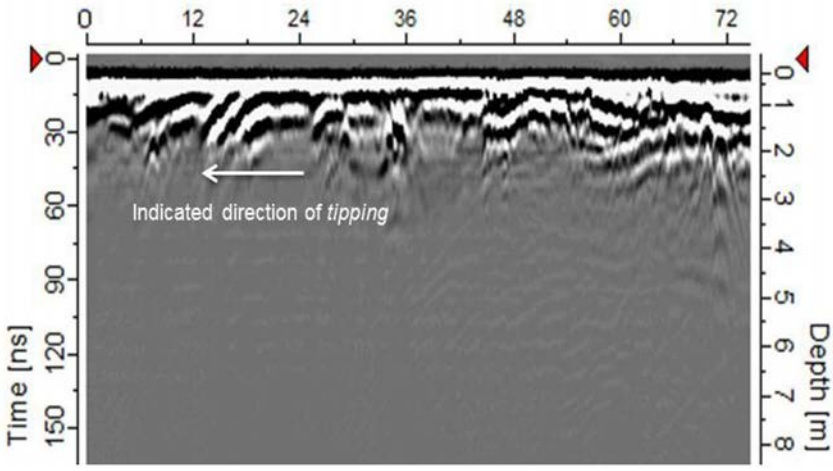


FIG. 8.46. Example transect with a 100 MHz antennae (bedrock below ca. 2–3 m) [8.46].

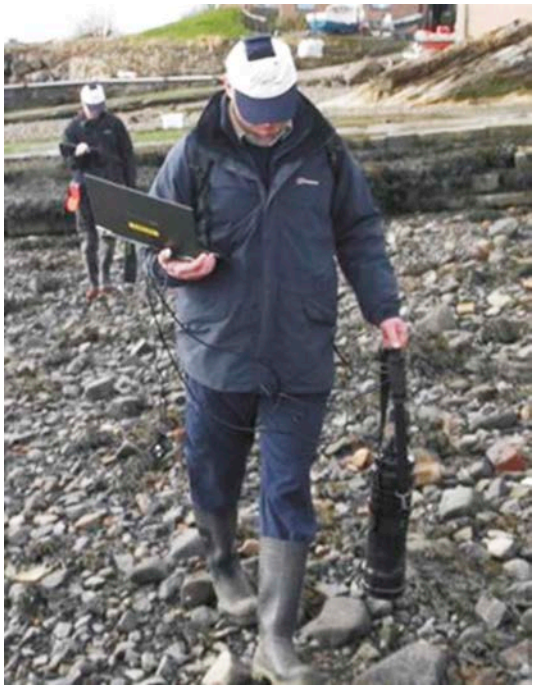
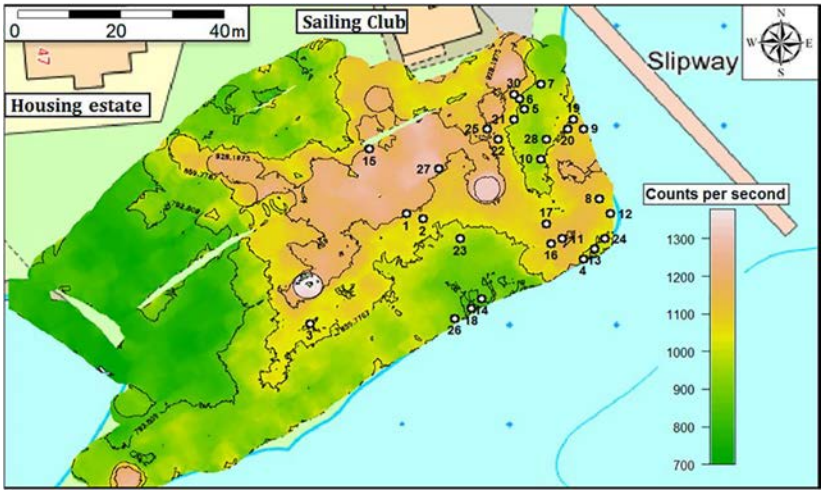


FIG. 8.47. Mobile gamma spectrometry system deployed at Dalgety Bay using NaI(Tl) and LaBr based detector systems.



Source: Figure 3 of Ref. [8.47].

FIG. 8.48. Map constructed from mobile gamma spectrometry data for the Dalgety Bay headland.

Source: Figure 4 of Ref. [8.46].

FIG. 8.49. Site excavation for the sampling and recovery of ^{226}Ra contaminated soil and artefacts on the Dalgety Bay headland.

Each excavation area was cordoned off and signage used to keep the public away from each excavation site.

A combination of all these data sets was used to locate the augured holes to penetrate into the site. Varley et al. [8.47] report that "Cores were not necessarily concentrated around the highest surface signal as indicated by the *in situ* survey (Fig. [8.48]), as surface sources and contaminated material were recovered from many of these locations." The complexity of the waste infill, including concrete blocks, necessitated a combination of digging and auguring and in some cases limited the ability to penetrate deep into the site. When obstacles were encountered, careful manual digging was used to further excavate the site. Tyler [8.46] reports:

> "Prior to the commencement of any excavation or coring work, the site and coring location was surveyed with a 48 mm diameter magnetometer, which was also deployed down a auger hole with a nominal 60 mm diameter. The magnetometer was deployed by an RPS Explosives Safety Engineer who surveyed the site for the presence of ferro-metallic objects."

Samples of infill were collected for subsequent analysis. A 51 mm diameter NaI(Tl) encased in plastic tubing was lowered down each augured hole to a depth of 2 m. A minimum of 600 s counts were acquired at 100 mm to 200 mm depth increments [8.47]. Varley et al. [8.47] find:

> "Here a novel method is proposed to tackle this issue based upon the interrogation of characteristic Monte Carlo calibration spectra using a combination of Principal Component Analysis and Artificial Neural Networks. The technique demonstrated that it could reliably distinguish spectra that contained contributions from point sources from those of background or dissociated contamination (homogenously distributed)."

The excavation of the site also revealed the presence of macropores, which under favourable hydrological conditions may act as a conduit for the movement of material. Since this demonstration, further site investigations have been undertaken by contractors of the Ministry of Defence to further delineate the extent of the contamination and the potential routes and mechanisms which can lead to public exposure [8.43, 8.44].

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Annex

SUMMARY OF SAMPLING PROGRAMMES AND STRATEGIES

Tables A–1 to A–4 summarize the sampling programmes implemented after the accidents at the Chernobyl nuclear power plant and the Fukushima Daiichi nuclear power plant.

A–1. SAMPLING STRATEGIES FOR LARGE SCALE SOIL MAPPING FOLLOWING THE ACCIDENT AT THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANT

To supervise the radiation exposure to workers in the investigation, at least one member of every team was equipped with an electronic personal dosimeter and the total radiation dose value at each sampling site was recorded. Each team verified the items listed in Table A–5 required for soil sampling. A checklist of required actions included the following:

— Prior permission for monitoring on private land;
— No radiation shielding material (i.e. cars and buildings) within 5 m from the monitoring point;
— No drastic change (i.e. several fold increase or decrease) in dose equivalent rate within 3 m × 3 m from the monitoring point;
— Labelling of sample information on container surface and sample bags;
— Decontamination of containers and samplers after sampling;
— Photographing soil sampling points and surrounding environment.

TABLE A–1. ACUTE (EMERGENCY) PHASE: SAMPLING PROGRAMMES FOR EMERGENCY RESPONSE AND COUNTERMEASURES IMPLEMENTATION FOLLOWING THE ACCIDENT AT THE CHERNOBYL NUCLEAR POWER PLANT

Mapping: Goal	Concept	Sampling approach	Sampler	Support to selection sampling points	Single/ composite sample	Ref.
Any territory: Identification of contamination density	Grid steps and boundaries selected based on airborne survey and dose rate measurement	Systematic grid 1 sample from 10 km (in 1986), 1 km (in 1991)	Ring* Ø140 mm Depth 50 mm	Air dose measurements	Single or composite 3–4 samples 20 cm × 20 cm	[A–1 to A–4]
Settlements: Identification of contamination density	Based on consideration of individual settlements combined with dose rate measurements	Stratified sampling In case of homogenous contamination, only 5 samples taken 4 samples taken at perimeter and one in the centre	Ring Ø140 mm Depth 50 mm	Air dose measurements Additional sampling points taken where external dose rate ×2 > than average	Single	[A–3, A–4]
Agricultural areas: Identification of contamination density and activity concentrations in soil and plants	Based on consideration of individual fields combined with dose rate measurements	Stratified sampling In case of homogenous contamination, only 10 samples (total mass ~2 kg) taken from ≥50 ha 1 sample unit per farm	Borer Ø20–60 mm Shovel Depth of arable layer ~18–22 cm	Air dose measurements Additional sampling points taken where external dose rate ×2 > than average	Composite	[A–1, A–4]

Forest: Identification of contamination density and activity concentrations in soil and plants	Based on consideration of individual quarter of the forest combined with dose rate measurements	Stratified sampling In case of homogenous contamination, only 5 samples taken from every quarter of the forest	Core Ø40 mm Depth 150 mm	Air dose measurements Additional sampling points taken where external dose rate ×2 > than average	Composite	[A–1, A–2]
Meadow: Identification of contamination density and activity concentrations in soil and plants	Based on consideration of individual fields combined with dose rate measurements	Stratified sampling In case of homogenous contamination, only 1 sample taken from ≥50 ha	Ring* Ø140 mm Depth 50 mm	Additional sampling points taken where external dose rate ×2 > than average	Single	[A–4]
Vegetation: Identification of activity concentrations in soil and plants		Stratified sampling In case of homogenous contamination, only 5 samples taken from sampling unit	1 m × 1 m	Air dose measurements	Composite	[A–1, A–2]

* These rings are the segments of the steel pipe sharpened at one edge. The ring is hammer into the soil and then pulled back with soil inside of it. The sample is packaged to maintain integrity without mixing. The activity of each sample is measured twice in a gamma spectrometer (the ring with soil is inverted after the first measurement).

TABLE A–2. LONG TERM PHASE: SAMPLING PROGRAMMES FOR ENVIRONMENTAL MANAGEMENT FOLLOWING THE ACCIDENT AT THE CHERNOBYL NUCLEAR POWER PLANT

Mapping: Goal	Concept	Sampling approach	Sampler	Support to selection sampling points	Single/ composite sample	Ref.
Whole territory: Identification of contamination density	Based on systematic grid Grid steps and boundaries are selected from goal and available information based on the optimization of funds, time, resources, etc. Typical contamination grid steps 0.1–1 km	Stratified sampling In case of homogenous contamination, ≥5 samples taken from sampling unit (≥ 100 m × 100 m)	Core Ø40 mm Depth 200 mm	Additional sampling points taken between sampling points where external dose rate > than average (30%)	Composite	[A–5, A–6]
Settlements: Identification of contamination density	Based on consideration of individual settlements combined with dose rate measurements (in every yard: inside the house and near it; in the garden, vegetable garden, etc.) In small villages, dose rates measured at least in 5 points of every yard, starting from its entrance In medium sized villages, dose rates measured in each third yard In large villages, dose rates measured in each fifth yard	Stratified sampling In case of homogenous contamination in the settlements with maximum 350 yards, 10 samples for gamma spectrometry taken, and for every 35 yards above this number 1 sample For the radiochemical analysis of ^{90}Sr, 5 samples taken for every 350 yards	Ring Ø140 mm Depth 50 mm Core Ø40 mm Depth 200 mm	Additional sampling points taken where external dose rate > than average (30%)	Composite	[A–1, A–7, A–8]
Farmland: Identification of contamination density and activity concentrations in soil and plants	Based on consideration of individual fields combined with dose rate measurements (distance between routes 100 m)	Stratified sampling In case of homogenous contamination, only 5 samples taken from fields ≤ 5 ha	Core Ø40 mm Depth 200 mm	Additional sampling points taken where external dose rate > than average (30%)	Composite	[A–1, A–2, A–7, A–8]

Forest: Identification of contamination density and activity concentrations in soil and plants	Based on consideration of individual quarter of the forest combined with dose rate measurements	Stratified sampling In case of homogenous contamination, only 5 samples taken from every quarter of the forest	Core Ø40 mm Depth 200 mm	Additional sampling points taken where external dose rate ×2 > than average	Composite	[A–1, A–2]
Meadow: Identification of contamination density and activity concentrations in soil and plants	Based on consideration of individual fields combined with dose rate measurements	Stratified sampling In case of homogenous contamination, only 5 samples taken from fields ≤ 5 ha	Core Ø40 mm Depth 200 mm	Additional sampling points taken where external dose rate ×2 > than average	Composite	[A–1, A–2]
Virgin soil: Identification of vertical distribution in soil	Based on consideration of individual fields combined with dose rate measurements	In case of homogenous contamination, ≥3 vertical samples taken from sampling unit After sampling, soil core cut with knife (starting with least contaminated bottom) into cylinders with height 1–5 cm, depending on task	Special cylindrical samplers, two separable parts placed in the tube Ø55 mm Length 200 mm		Single sample, each layer	[A–1, A–2]
Vegetation: Identification of contamination density and activity concentrations in soil and plants	Plant samples taken directly from agricultural land, in the same areas as the soil samples	Stratified sampling If contamination evaluated only for vegetation, point samples selected at the diagonal fields or along the broken line passing through the area of the field For the composite sample of plants with a weight of 0.5–1 kg (fresh weight), 8–10 point samples selected	1 m × 1 m 2 m × 2 m		Composite	[A–1, A–2]

TABLE A–3. ACUTE (EMERGENCY) PHASE: SAMPLING PROGRAMMES FOR EMERGENCY RESPONSE AND COUNTERMEASURES IMPLEMENTATION FOLLOWING THE ACCIDENT AT THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANT

Mapping: Goal	Concept	Sampling approach	Sampler	Single/composite sample	Additional data gathered	Ref.
Whole territory: Identification of contamination density and calibration of airborne monitoring	Grid steps and boundaries selected based on airborne survey Emergency soil sampling for the mapping the deposition density of $^{134,137}Cs$, ^{131}I, $^{89,90}Sr$, ^{110m}Ag, $^{238,239,240}Pu$, ^{129m}Te	Based on systematic grid 1 sampling point from 2 km for 80 km radius 10 km outside of 80 km radius*	Ring Ø50 mm Depth 50 mm	Single Measured all 5 samples in every sampling units 2183 units along whole sampling area	Geographical coordinates Detailed dose measurement Soil and land use type	[A–9, A–10]
Farmland: Identification of contamination density	Evaluate Cs contamination density (Bq/kg) in farmland	Standard sampling depth 150 mm Varies according to plough depth 10–300 mm	Ring Ø50 mm Depth 300 mm Screw dig core sampler	Composite 5 samples 3461 units along whole sampling area	Land use type Planted crop species Date of last ploughing Depth of ploughing Soil group	[A–11, A–12]
Forest: Identification of contamination density	Evaluate Cs inventory in litter and soil 5 months after accident	Based on systematic grid1 sample from 4 km for 80 km radius 10 km outside of 80 km radius Samples from 4 points (north, south, east and west of a tree trunk)	Ring Ø50 mm Depth 50 mm Litter collected separately	Composite 4 samples 391 units along whole sampling area	Tree species Dose level at 1 m	

Riverbank and shore: Identification of contamination density	Cs concentration in riverbank and shore	Samples selected from environmental monitoring points Samples from both banks and rivers	Ring Ø50 mm Depth 50 mm	Composite 5 samples 724 units along whole sampling area	Dose level at 1 m	**
Various land use: Identification of contamination density	Effect of land use on initial depth distribution	Vegetation samples cut with scissors from a sampling area of 30 cm × 30 cm or 50 cm × 50 cm Frozen (−30°C) soil cores cut into 5 sections 0–1 cm, 1–3 cm, 3–5 cm, 5–10 cm, >10 cm depth intervals	Ring Ø100 mm Depth 300 mm	Composite 6 samples 15 units along whole sampling area	Grain size	[A–13]

* To prevent possible loss of iodine, the samples were sealed and not dried before the measurement of the radioactivity.

** See www.env.go.jp/en/water/rmms/result_pw-fy2011.html

TABLE A–4. LONG TERM PHASE: SAMPLING PROGRAMMES FOR ENVIRONMENTAL MANAGEMENT FOLLOWING THE ACCIDENT AT THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANT

Mapping: Goal	Concept	Sampling approach	Sampler	Single/composite sample	Additional data gathered	Ref.
Whole territory: Identification of contamination density	Selected from the grid of soil sampling by MEXT and monitor the change of depth profiles 2–3 sampling per year, starting Nov. 2011	Repeated sampling 5 mm intervals to depth 20 mm 10 mm intervals at depth 20–50 mm 30 mm intervals at depth 50–80 mm	Scraper plate 150 mm × 300 mm	Single 86 units along whole sampling area		
Farmland: Identification of contamination density	Detailed initial depth distribution of ^{134,137}Cs and ^{131}I	Flat, unvegetated and non-cultivated farmland 5 mm intervals up to depth 50 mm 10 mm intervals at depth 50–100 mm 20 mm intervals at depth 100–300 mm	Scraper plate 150 mm × 300 mm	Single	Grain size	[A–14] *
Paddy field: Identification of contamination density	Depth distribution of ^{134,137}Cs and ^{131}I in paddy field before and after tillage	Uppermost soil surface layer (1 cm) collected in advance sliced 1 cm intervals to depth 5 cm 2.5 cm intervals to depth 10 cm 5 cm intervals to depth 15 cm**	Ring Ø80 mm Ø150 mm Depth 150 mm Screw dig core sampler	Composite 5 samples	Dust collection	[A–15] *
Riverbank and lake shore	Cs concentration in riverbank and lakeshore 2–4 sampling/year	Samples in selected environmental monitoring points Samples collected from both riverbanks	Ring Ø50 mm Depth 50 mm	Composite 5 samples >1000 units along whole sampling area	Dose level at 1m	*
Various land use: Identification of contamination density	Change of depth distribution in different land use of ^{137}Cs 2–3 sampling/year	Establish fence to protect site	Scraper plate 150 mm × 300 mm	Single 8 units along whole sampling area	Soil type Grain size	[A–16] *

* See www.env.go.jp/en/water/rmms/surveys.html

** Soil from the outermost 5 mm of the soil core wall was removed to avoid contamination from the upper layer of soil.

TABLE A–5. REQUIRED HAND HELD ITEMS FOR SOIL SAMPLING AND AIR DOSE RATE MEASUREMENT

Item/purpose	Details
Acquisition and verification of location information	Map of survey site GPS information
Soil collection tools	U8 container Soil collection assist device 100 cm^3 cylindrical sample tubes Small shovel or trowel Plastic knives (disposal) Wooden mallet (or metal hammer) Mixed use polyethylene bags Sealable polyethylene bags to hold the samples Labels (filled out with grid cell ID number of survey site of collected sample and attached) Cardboard boxes (each for packaging of collected samples from the same survey site)
Tools for soil collection at depth 30 cm	Metal pipe (30 cm) Cap for use with metal pipe and steel rods Wooden board
Contamination prevention and decontamination tools	Moistened hand towel (disposable) Wet wipes Wet paper rags Gloves (cotton and rubber) Masks Garbage bags (for disposal of used gloves and polyethylene bags)
Dose measurement tools	NaI(Tl) scintillation survey meter (calibrated) Ionization chamber survey meter (calibrated) (only for teams that might perform measurements at survey sites with an air dose rate > 30 μSv/h)
Equipment for height alignment	Equipment that can measure a height of 1 m from the ground surface (camera tripod. tape measure, rope) Tape measure (50 m long)
Supervision of radiation dose exposure	Electronic personal dosimeter

After soil sampling, data were recorded in operation records made at the time of air dose rate measurement and soil collection at each site (for an example, see Fig. A–1). These documents include the following:

— Teams that conducted the operation and their members;
— Date and time of the measurement (collection);
— Location information of the survey site such as latitude and longitude data measured by GPS, the address and facility;
— For air dose rate measurements, survey meter used (model, manufacturer's serial number and service number), measured air dose rate, calibration constant and weather;
— For soil collection, identification number of the collection site's grid cell, collecting personnel, working conditions of the land plot and the exterior dose rates of all containers;
— At soil collection locations, a rough sketch of any significant landmarks (e.g. facilities) and their range from the site (see Fig. A–2);
— Pictures of the panoramic view, sampling location and surface condition for the record of collection (see Fig. A–3).

Team name		Date of measurement/sampling	/ / / (MM/DD/YY)
Name of members	1 2 3		: (AM/PM)
Location	Latitude (N)		Longitude (E)
Address			
		Confirmed by	

.....

Types and serial number Information of measurement device	NaI(Tl) scintillation detector Ionization chamber type (>30 μSv/h) Type: Serial Number:	Measurement method	Gamma ray: Survey meter method
		Background level	(μSv/h)
		Calibration Constant (calibration date) (Radiation source for Calibration) (Expiration date)	/ / (MM/DD/YY) ( ) / / (MM/DD/YY)

.....

Measured value (μSv/h)	Ambient dose equivalent rate (μSv/h)	Notes (i.e. climate)	Confirmed by

.....

Soil sampling No.		Sampled by	
Container type	U-8 container	Ambient dose equivalent rate (on the surface of the sampling container)	μSv/h
Soil type (container photography)	Completed		
Land use type	Paddy field; rove (orchard, mulberry plantation, tea plantation)		
	Pasture and meadow, wasteland, bare land		
	Other: (Land use type:)		

FIG. A–1. Examples of operation records.

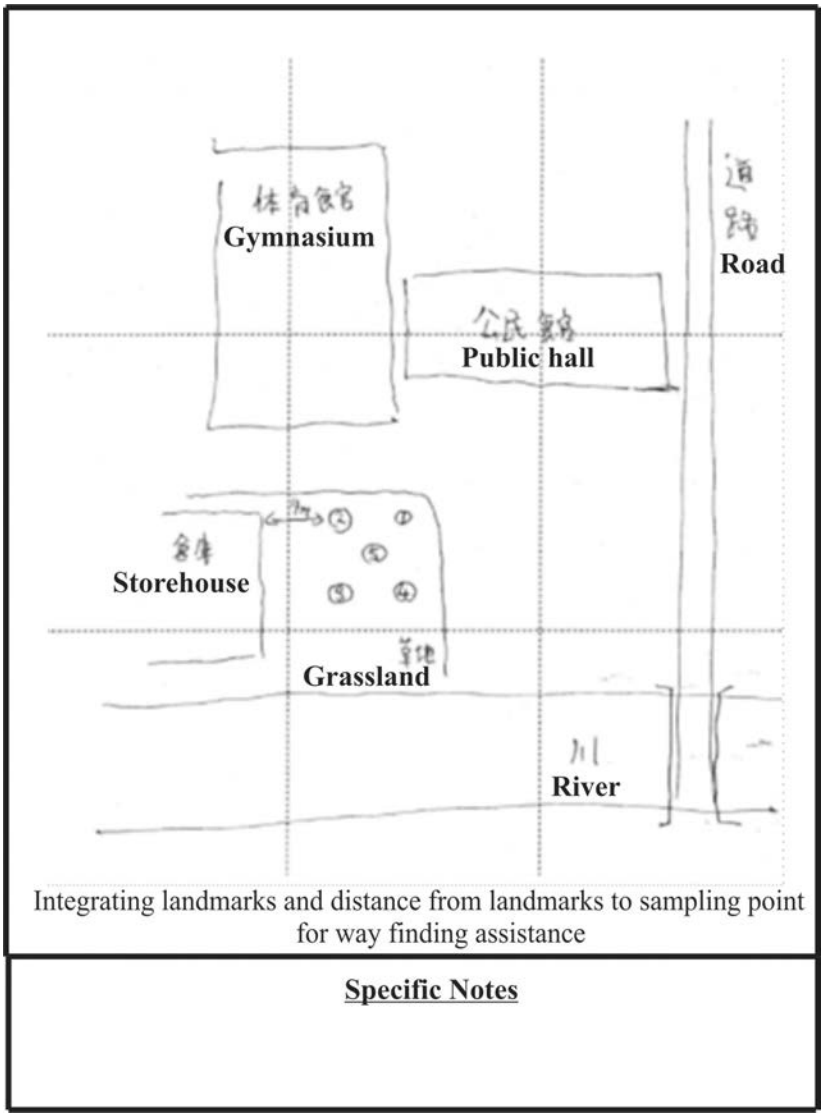

FIG. A–2. Rough sketch of landmarks.

NO.

panoramic view

NO.

Collection location

NO.

surface layer condition

FIG. A–3. Soil collection location photographs.

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ABBREVIATIONS

EPA	United States Environmental Protection Agency
FDNPP	Fukushima Daiichi nuclear power plant
FSA	Food Standards Agency
FSS	Food Standards Scotland
GIS	geographic information system
ICRU	International Commission on Radiation Units and Measurements
ISO	International Organization for Standardization
NORM	naturally occurring radioactive material
Roshydromet	Federal Service for Hydrometeorology and Environmental Monitoring
Rosleskhoz	Federal Agency for Forestry
SEPA	Scottish Environment Protection Agency

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