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Programmes and Systems for Source and Environmental Radiation Monitoring

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PROGRAMMES AND SYSTEMS FOR SOURCE AND ENVIRONMENTAL RADIATION MONITORING

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FOREWORD

The discharge of radionuclides to the atmosphere and aquatic environments is a legitimate practice in the nuclear and other industries, hospitals and research. Where appropriate, monitoring of the discharges and of relevant environmental media is an essential regulatory requirement in order to ensure appropriate radiation protection of the public. Such monitoring provides information on the actual amounts of radioactive material discharged and the radionuclide concentrations in the environment, and is needed to demonstrate compliance with authorized limits, to assess the radiation exposure of members of the public and to provide data to aid in the optimization of radiation protection.

Uncontrolled releases of radionuclides to the atmosphere and aquatic environments may occur as a result of a nuclear or radiological accident. Again, monitoring at the source of the release and of the environment is necessary. In this case, monitoring is used both to assess the radiation exposure of members of the public and to determine the actions necessary for public protection, including longer term countermeasures.

Source and environmental monitoring associated with the release of radionuclides to the environment is the subject of a number of IAEA Safety Standards, particularly IAEA Safety Standard RS-G-1.8 (Environmental and Source Monitoring for Purposes of Radiation Protection). This publication is intended to complement this Safety Guide and, by so doing, replaces Safety Series No. 41 (Objectives and Design of Environmental Monitoring Programmes for Radioactive Contaminants) and Safety Series No. 46 (Monitoring of Airborne and Liquid Radioactive Releases from Nuclear Facilities to the Environment). Like Safety Standard RS-G-1.8, this Safety Report deals with monitoring at the source and in the environment associated with authorized releases of radionuclides to the environment. It also deals with the general issues of emergency monitoring during and in the aftermath of an accidental release of radionuclides, in particular, the general aspects of monitoring for long lived radionuclides that might be widely dispersed in the environment as a consequence of an accident. More detailed information on monitoring during emergencies is presented in other IAEA publications.

This report provides information on practical considerations affecting the design and operation of monitoring programmes and systems in accordance with the relevant IAEA Safety Standards. It deals with the whole spectrum of facilities, whether nuclear or non-nuclear, in which radioactive material is used. The intended audience includes national regulatory bodies, and other agencies and organizations involved in the design and operation of source and environmental radiation monitoring programmes and systems; experts involved in the assessments of public exposure based on the results of monitoring

programmes; and operators of nuclear facilities and other facilities from which radionuclides might be released to the environment or direct radiation may lead to public exposure.

The IAEA wishes to express its gratitude to all those who assisted in the drafting and review of the report. The IAEA officer responsible for this publication was V. Berkovskyy of the Division of Radiation, Transport and Waste Safety.

EDITORIAL NOTE

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1. INTRODUCTION

1.1. BACKGROUND

Exposure of members of the public to radiation in planned exposure situations should be considered, as appropriate, as: (a) normal exposure and potential exposure assessed prospectively at the design or planning stages; and (b) exposure assessed retrospectively with the use of results of source and environmental monitoring programmes.

Facilities or activities that use radioactive material generate a variety of radioactive gaseous and liquid residues, which need to be managed in a safe manner. In some cases, it may be appropriate to release such residues to the atmospheric and aquatic environments. Releases to the environment that are authorized and undertaken in a planned and controlled manner in this report are referred to as 'discharges' (see also Ref. [1]). Releases of radionuclides to the atmosphere and the aquatic environment may also occur as a result of a nuclear or radiological accident but, in this case, the release will take place in an uncontrolled manner. Both 'discharge' and 'release' are terms that relate to a process. However, in the context of the IAEA Safety Standards, they are also used to describe the material involved [1]. The word 'effluent' means 'flowing out or forth' and is also used to mean the actual material being discharged to the environment. To avoid any possible confusion, however, it will not be used in this report. The term 'contamination' used in this publication refers only to the presence of radioactivity and gives no indication as to the magnitude of the hazard involved.

Exposure of members of the public due to a facility or activity may arise from: (a) the dispersal of released radionuclides in the environment, which may cause the external and internal exposure; and/or (b) the direct emission of radiation from the source, which causes the external exposure. Such radiation will be referred to in this report as 'direct radiation'.

The exposure pathways from releases include external radiation exposure due to radionuclides in the plume and deposited on the ground, inhalation of airborne radionuclides in the plume or due to resuspension of ground deposits, and ingestion of contaminated foodstuffs. Members of the public need to be

appropriately protected against the exposure arising from these pathways. Monitoring[1] is an important tool for this purpose.

In 1996, the IAEA, jointly with five other international sponsoring organizations, published the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (hereinafter referred to as the Basic Safety Standards or BSS) [2]. This report establishes the basic requirements for protection against the risks associated with exposure to ionizing radiation and for the safety of radiation sources and, in particular, establishes the basic requirements for radiation monitoring in the context of discharge control to check for compliance with the authorized discharge limits and to permit estimation of the exposure of a representative person[2]. The Basic Safety Standards [2] also establishes basic requirements for radiation monitoring and assessment in emergency exposure situations. The radiation protection of the public and environment and associated monitoring are also included in the scope of a number of international treaties [3].

Since the publication of the BSS, separate Safety Requirements have been developed that have some relevance to the releases of radioactive material to the environment. These are:

— Legal and Governmental Infrastructure for Nuclear, Radiation, Radioactive Waste and Transport Safety [4];
— Preparedness and Response for a Nuclear or Radiological Emergency [5];
— The Management System for Facilities and Activities [6];
— Near Surface Disposal of Radioactive Waste [7];
— Predisposal Management of Radioactive Waste, Including Decommissioning [8].

A number of Safety Guides elaborate on these requirements, notably the Safety Guide on Regulatory Control of Radioactive Discharges into the

[1] The term ‘monitoring’ is used in this report to mean the measurement of some radiation protection quantity, such as ambient dose equvalent or activity of radionuclides in enironmental media, related to the assessment or control of exposure to radiation or radioactive substances. It also includes the interpretation of the measurement results and assessments of the exposure.

[2] A representative person is defined in the following report by the International Commission on Radiological Protection (ICRP): Publication 101 cites “an individual receiving a dose that is representative of the more highly exposed individuals in the population”. ICRP Publication 101 also indicates that the dose to a representative person “… is the equivalent of, and replaces, the mean dose in the ‘critical group’ ”, and provides guidance on assessing doses to the representative person.

Environment [9], which is mainly concerned with the principles and procedures to be followed in establishing authorizations for the discharge of radioactive materials; and the Safety Guide on Environmental and Source Monitoring for Purposes of Radiation Protection [10], which elaborates on the requirements for source, environmental and, to a lesser extent, individual monitoring. The latter Safety Guide supersedes two earlier Safety Series reports, the first dealing with Objectives and Design of Environmental Monitoring Programmes for Radioactive Contaminants [11], and the second with Monitoring of Airborne and Liquid Radioactive Releases from Nuclear Facilities to the Environment [12].

This Safety Report complements a number of other Safety Reports, namely:

— Assessment of Doses to the Public from Ingested Radionuclides [13];
— Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment [14];
— Monitoring and Surveillance of Residues from the Mining and Milling of Uranium and Thorium [15];
— Surveillance and Monitoring of Near Surface Disposal Facilities for Radioactive Waste [16].

This Safety Report takes account of relevant guidance provided by the International Commission on Radiological Protection (ICRP), in particular, that given in ICRP Publication 43, Principles of Monitoring for the Radiation Protection of the Population [17], and ICRP Publication 101, Assessing Dose of the Representative Person for the Purpose of Radiation Protection of the Public [18].

1.2. OBJECTIVE

The objective of this Safety Report is to provide detailed practical information on the design and operation of source and environmental monitoring programmes and systems in relation to:

— The control of radionuclide releases and public exposure due to direct radiation from both nuclear and non-nuclear facilities;

— Emergency and existing exposure situations, such as nuclear or radiological emergencies or the past contamination of areas with long lived radionuclides[3].

The target users of the report are designers and operators of source and environment radiation monitoring systems and the national regulatory bodies.

1.3. SCOPE

This report deals with the design and operation of source and environmental monitoring programmes and systems relating to the release of radioactive material to the environment from authorized (registered or licensed[4]) practices under normal operating conditions and during the decommissioning of facilities. The practices considered include nuclear facilities (power plants, research reactors, reprocessing plants, fuel production plants, radioisotope production plants, uranium and thorium mining and milling facilities, near surface disposal facilities for radioactive waste) and non-nuclear facilities, for example, hospitals, research and educational establishments, and plants that handle naturally occurring radioactive material (NORM). It also deals with monitoring sites contaminated as a consequence of past practices. It does not, however, deal in detail with the monitoring and surveillance of residues from the mining and milling of uranium and thorium, as this is a matter covered in a separate Safety Report [15], or the surveillance and monitoring of near surface disposal facilities for radioactive waste, as this is covered in a further Safety Report [16].

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[3] Consistent with IAEA Safety Standards Series No. RS-G-1.8 [10], the term 'long lived radionuclide' is applied to radionuclides with half-lives of 30 years or more (e.g. ^{137}Cs), in contrast to the usual terminology in waste safety, where this term is usually used for radionuclides with half-lives of 1000 years or more.

[4] Two forms of authorization of practices are specified in the BSS [2], namely, registration and licensing. Registration, if it is used, applies to practices of low or moderate risks, while licensing is used for those practices that present more significant risks. These words reflect the general principle that there is a need to apply a graded approach to the control of radiation hazards. Often, however, licensing is the only word used in national legislative and regulatory systems. In this document, the generic word 'authorization' is used except when there is a need for a distinction to be made between practices that present different levels of risk, in which case the terms 'registration' and 'licensing' (and their corresponding adjectival equivalents) will be used.

The report discusses general issues related to the design and operation of monitoring systems during and in the aftermath of a nuclear or radiological accident. In particular, it deals with monitoring for long lived radionuclides widely dispersed in the environment following an accidental release. However, the material that is given here should be read in conjunction with the more detailed information given in other publications that deal with emergency preparedness and response [19–23].

In general, individual monitoring of members of the public is not undertaken. However, there may be occasions where this is necessary, particularly following an accidental release, so this matter is also discussed in the report.

This Safety Report does not deal with the monitoring of workers and the workplace. Guidance on such monitoring is provided in a number of IAEA Safety Standards [24–27]. It also does not address monitoring for technological and research purposes that are not related to the protection of members of the public, or monitoring of the global fallout of radionuclides during past nuclear weapons tests, which are unamenable to control.

1.4. STRUCTURE

A framework for the design and operation of source and environmental monitoring programmes and systems is given in Section 2. It covers the objectives of such programmes and systems, the relevant regulatory requirements, and the roles and responsibilities of those involved. Section 3 deals with the design of source monitoring programmes, the types of source measurement techniques and the specific aspects of monitoring related to discharges to the atmosphere and aquatic environments. Section 4 deals with the design of environmental monitoring programmes, covering the monitoring of air and the terrestrial and aquatic environments. Section 5 deals with some of the specific issues related to monitoring during and after an accidental release of radioactive material. Section 6 additionally discusses generic aspects of monitoring programmes, covering issues such as sampling, laboratory sample analysis, detection limits and uncertainties, quality management systems, calibration of equipment and record keeping. Section 7 gives an outline of dose assessments procedures based on monitoring data and the reporting of information to the regulatory body. Six appendices contain technical examples and details of: (a) monitoring programmes, equipment and procedures for different types of facilities (Appendices I–III); (b) exposure pathways and dose assessments (Appendix IV); (c) characterization of the size and biological solubility of radioactive aerosols (Appendix V); and (d) examples of results of

source and environmental monitoring programmes (Appendix VI). Due to technical limitations, the examples and discussions given in the appendices are not, and cannot be regarded as, all-inclusive.

2. FRAMEWORK FOR THE DESIGN AND OPERATION OF SOURCE AND ENVIRONMENTAL MONITORING PROGRAMMES AND SYSTEMS

2.1. REGULATORY REQUIREMENTS

2.1.1. Planned exposure situations: Discharges from authorized practices

The requirements relating to the discharge of radionuclides to the environment are given in Refs [2, 4, 8]. Those relating to uncontrolled releases of radionuclides are given in Refs [2, 4, 5]. Guidance is given in a number of Safety Guides [9, 10] and other reports [13, 14, 16].

The principal requirement relating to the discharge of radionuclides to the environment is that the person responsible for the practice giving rise to the discharge should, unless exempt, apply to the regulatory body for authorization[5] [2, 4]. The authorization is required to take the form of a registration or a licence, depending on the degree of hazard associated with the practice. Exemption only applies to practices that present radiation risks to individuals that are 'sufficiently low as to be of no regulatory concern' [2]. An important point from this requirement is that the regulation of practices should be graded according to the

[5] A number of terms are used in the IAEA Safety Standards to describe the person responsible for a practice. The BSS [2] uses the term 'legal person' meaning 'any organization, corporation, partnership, firm, association, trust, estate, public or private institution, group, political or adminstrative entity or other person designated in accordance with national legislation who or which has responsibility and authority for any action having implications for protection and safety'. Other documents (e.g. Ref. [4]) use the term 'operator' to mean 'any organization or person applying for authorization or authorized and/or responsible for nuclear, radiation, radioactive waste or transport safety when undertaking activities or in relation to any nuclear facilities or sources of ionizing radiation'. This includes, inter alia, private individuals, governmental bodies, consignors or carriers, licensees, hospitals and self-employed persons.

degree of radiation risk that they present. This graded approach applies irrespective of whether the legislative system within a country actually makes a distinction between registration and licensing.

Where both forms of authorization are used, registration is normally applied to practices for which: (a) safety can largely be ensured by the design of the facilities and equipment; (b) the operating procedures are simple to follow; (c) the safety training requirements are minimal; and (d) there is a history of few problems with safety in operations. It is best suited to those practices for which operations do not vary significantly. Licensing would then apply to more complex practices that have the potential for causing more significant exposure of workers and members of the public.

Registrants and licensees are required to ensure that radioactive material is not discharged to the environment unless [2]:

(a) The discharge is within the discharge limits authorized by the regulatory body;
(b) Discharges are controlled;
(c) Public exposure caused by the discharges is limited;
(d) Control of the discharges is optimized.

The BSS [2] also requires registrants and licensees to:

(a) Determine the characteristics and activity of the material to be discharged;
(b) Determine all significant exposure pathways by which the discharged radionuclides can deliver public exposure;
(c) Assess the doses to the representative person due to the planned discharges;
(d) Submit the information to the regulatory body.

All authorized practices are required to be carried out in accordance with the conditions specified in the authorization given by the regulatory body. These will, in general, include a requirement to minimize as far as practicable the discharge of radioactive material to the environment. Compliance with this basic principle of radiation protection is mainly attained by good design of the nuclear facility, including the provision of efficient retention systems for radioactive materials and careful adherence to good operational procedures. In addition, the conditions will generally specify the type of monitoring of the discharge and the environment that should be carried out.

During the operational stages, the authorized person is required, among other things, to monitor the discharges with sufficient detail and accuracy to demonstrate compliance with the authorized discharge limits and to permit an estimate to be made of the exposure of the representative person. They are also

required to record the monitoring results and estimated exposures, and to report the monitoring results to the regulatory body at approved intervals, and when any discharges exceed the authorized discharge limits.

Discharges to the environment are also included in the framework of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [28]. Contracting Parties of the Joint Convention are required to take appropriate steps to ensure that radioactive discharges to the environment are limited.

All of the above requirements either explicitly or implicitly indicate the need for authorized persons to consider what monitoring programmes should be undertaken in order to fulfil regulatory requirements. According to IAEA Safety Standards Series No. RS-G-1.8 [10], monitoring should be carried out for licensed facilities and may need to be carried out for registered facilities. Safety Guide No. WS-G-2.3 [9] goes further and recommends that routine monitoring programmes should be required for most, if not all, nuclear fuel cycle facilities, from uranium mining and milling to the reprocessing of spent nuclear fuel. They should also be set up for all other facilities that discharge significant amounts of radioactive material to the environment, including large nuclear medicine establishments, some research facilities and industries handling NORM. Routine monitoring programmes for these facilities not only are necessary to meet regulatory requirements, they also provide baseline data for the emergency monitoring programme, although not all of them require a full emergency monitoring capability.

There are many practices for which registration is appropriate and from which the direct radiation and discharges are low or do not occur at all, and the potential for a significant accidental release of radionuclides is either very low or non-existent. Consequently, both the normal exposure and potential exposure of the public are also low or non-existent. Examples of such registered practices are small research institutes, small hospitals and nuclear medicine clinics, where short lived radionuclides are predominantly used, and the corresponding discharges to the environment are very low. Some degree of monitoring at the source may, however, sometimes be required.

2.1.2. Emergency and existing exposure situations

Despite all the precautions taken in the design and operation of a facility, there is always the possibility that a failure or accident may lead to an emergency situation. In some cases, this may give rise to a release of radioactive material into the public domain, which may necessitate response actions. The IAEA Safety Standards require adequate preparedness to be established and maintained at local and national levels to respond to emergencies in order to reduce or avert

exposures [2, 4, 5]. It is also a responsibility of governments to ensure that the appropriate authorities have the necessary resources, and make preparations and arrangements to deal with any consequences of accidents in the public domain. These are required to include actions to be taken both during and after an emergency.

As with the normal operation of a practice, the arrangements for safety are required to be commensurate with the potential hazard and the nature of the hazard associated with the practice. Criteria for intervention in the event of an emergency should be established in advance and may include the use of predefined levels, such as intervention levels or action levels. The arrangements should include a clear allocation of responsibility for decision making and an effective means of communication. In addition, the resources and arrangements are taken to include those necessary for undertaking the appropriate monitoring to determine the radiological conditions and provide information to assist in decision making. Such monitoring would normally include the environment, foodstuffs, milk and people in the event of an emergency resulting in an off-site release of radioactive material [5].

Effective off-site emergency arrangements are required to be established for all nuclear facilities. In addition, there are situations where emergencies could occur in unforeseeable locations. Examples are non-authorized activities and transport accidents, both involving 'dangerous sources'[6], and the return to Earth of nuclear powered satellites [5].

The BSS requires all reasonable steps to be taken to assess exposure incurred by members of the public as a consequence of an accident and for the results of the assessments to be made publicly available [2]. These assessments are required to be based on the best available information. Furthermore, comprehensive records of the assessments and of the monitoring results are required to be maintained.

Other situations that may require intervention include those involving chronic, prolonged or existing exposure. 'Chronic exposure' is the term used in the BSS to refer to exposure persisting in time [2]. The term 'prolonged exposure' was introduced by the ICRP [29], since it was felt that this better reflected the intended meaning. More recently, the ICRP has introduced the term 'existing exposure' to qualify the word 'situation' in these cases [30]. These exposures include those from radioactive residues from past events, including accidents, past practices and sites contaminated by long lived radionuclides of natural origin (i.e. NORM). For such situations, a national strategy is required to be formulated to specify, prioritize and manage remediation situations and to ensure that an

[6] A 'dangerous source' is one that could, if not under control, give rise to exposure sufficient to cause severe deterministic effects [1, 5].

adequate legal and regulatory framework, supported where necessary by appropriate guidance material, is in place so that workers, the public and the environment are protected when remediation programmes are undertaken [2, 4, 31]. This strategy shall be commensurate with the risks associated with the contaminated areas and the approach to remediation shall be graded such that the actions to be taken can be prioritized according to the risks. Governments are required to appoint organizations to be responsible for making the necessary arrangements for intervention to ensure that remedial action is taken to protect the public. Appropriate intervention levels or action levels need to be established by the responsible national authorities. As with emergency exposure situations, monitoring of environmental contamination would normally be necessary in order to make appropriate comparisons with the intervention or action levels that have been established.

2.2. OBJECTIVES OF MONITORING

The primary objectives of any monitoring programme for protection of the public and the environment, as specified in IAEA Safety Standards Series No. RS-G-1.8 [10], are to:

(a) 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) Provide information and data for dose assessment purposes, and to assess the exposure or potential exposure of 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) 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.

Subsidiary objectives, which should usually be fulfilled by a monitoring programme, are to [10]:

(a) Provide information for the public;
(b) Maintain a continuing record of the impacts of a facility or a practice on environmental radionuclide levels;
(c) Check the predictions of environmental models so as to modify them as appropriate in order to reduce uncertainties in the dose assessment.

In summary, monitoring — where appropriate — should be regarded as an essential element of the control of discharges to ensure protection of the public and the environment. It is also an essential element in determining the actions that should be taken to protect the public in intervention situations. The following three types of monitoring are envisaged [1]:

(1) Source monitoring, which is monitoring of the activity of radioactive materials being released to the environment or of external dose rates due to sources within a facility or activity;
(2) Environmental monitoring, which is monitoring of the external dose rates due to sources in the environment and/or the radionuclide concentrations in environmental media;
(3) Individual monitoring, which is monitoring with equipment worn by individuals or measurements of the quantities of radioactive materials in or on their bodies.

Environmental monitoring can be subdivided into two general types: source related and individual related monitoring (see Fig. 1). The former relates to the determination of the impact of a particular source or facility; the latter relates to the determination of the total impact of all sources on an individual or group of individuals. This Safety Report is primarily concerned with the former although, if there are several significant sources affecting one individual or a group of individuals (e.g. several nuclear facilities discharging radioactive material into the same river system), individual related monitoring may also be necessary.

In almost all nuclear facilities, airborne discharges are through one stack or more, and liquid discharges are generally through a pipe or canal into an appropriate sewage system or directly into a body of water (e.g. sea, river or lake). The rates of discharge may vary. Airborne discharges are, for the most part, undertaken continuously, although in some facilities the discharges may be discontinuous (batch), for example, during shutdown operations. On the other hand, liquid discharges are often discontinuous, on a batch basis (e.g. liquid discharges from hospitals are often retained to allow for decay of

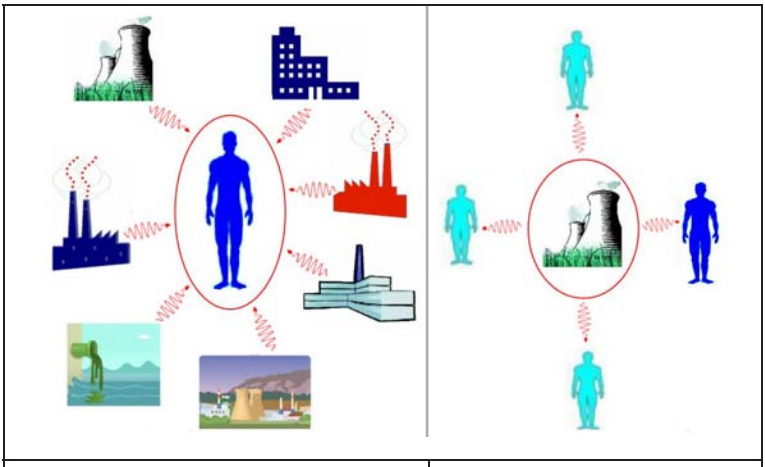

FIG. 1. A representation of: (a) individual related monitoring; and (b) source related monitoring.

the short lived radionuclides before discharge as a batch to a sewage system), and only a few radiologically less important discharges are undertaken continuously to the drainage system. Normally, all discharge points should be monitored.

2.3. ROLES AND RESPONSIBILITIES

The roles and responsibilities of authorized persons and regulatory bodies are established in the BSS [2] and Safety Guide No. RS-G-1.8 [10]. Table 1 outlines the major areas of responsibility for registrants, licensees and the regulatory body concerning the different types of monitoring. The following text summarizes the relevant material found in the IAEA Safety Standards.

2.3.1. Registrants and licensees

A fundamental principle is that the prime responsibility for safety lies with the registrant and licensee, and any action taken by the regulatory body does not reduce the responsibility of the registrant or the licensee in this respect [4, 32]. The responsibilities of the authorized person relating to the discharge of radioactive material are set out in Refs [2, 9, 10]. In particular, the registrant or licensee is required to comply with the applicable regulatory requirements. These

TABLE 1. RESPONSIBILITIES FOR ENVIRONMENTAL AND SOURCE MONITORING *(modified from Ref. [10])*

Exposure situations (category)	Type of source/exposure situation	Responsible body		
		Registrant	Licensee	Regulatory body or designated organization
Planned exposure situations (practice)	Excluded, exempt or cleared	No monitoring required		
	Registered sources	Source monitoring	Not applicable	Control measurements and review/verify dose assessments, as appropriate
	Licensed sources	Not applicable	Source and environmental monitoring, dose assessment	
	Multiple sources	Source monitoring	Source and local environmental monitoring	Environmental monitoring and dose assessment
Emergency and existing exposure situations (intervention)	Emergency exposure situations	Source monitoring	Source monitoring, near field environmental monitoring and individual monitoring of workers	Large scale and near field environmental monitoring; individual monitoring of the public as appropriate
	Existing exposure situations (chronic/prolonged)	Not applicable	Source and local environmental monitoring	Large scale and near field environmental monitoring; dose assessment as appropriate

will be set out in the authorization of the practice and the relevant legislation and regulations. In general, they will define the requirements relating to monitoring prior to the commencement of operation, the monitoring that should be undertaken during and after operation, and the reporting of the results of such monitoring. They will cover both source and environmental monitoring.

Usually registrants and licensees will have the following general responsibilities to:

(a) Prevent any unacceptable radiation or contamination hazard to the public resulting from the discharge;
(b) Comply with applicable regulatory requirements;
(c) Report to the regulatory body any changes to the discharge.

Specifically with regard to monitoring, the registrant and licensee should:

(a) Undertake all necessary pre-operational investigations, including appropriate monitoring.
(b) Provide the means for and perform adequate source and environmental monitoring programmes during and after operation that will permit unexpected releases to be detected promptly.
(c) Ensure that the source and environmental monitoring programmes provide data to:
    (i) Demonstrate that doses to the public are below the criteria established by the regulatory body for planned exposure situations;
    (ii) Estimate public exposure and to support protective and remediative actions in emergency and existing exposure situations.
(d) Report to the regulatory body any significant increases in discharges or in environmental contamination that could be attributed to releases from the sources under their responsibility.
(e) Establish and maintain appropriate equipment and programmes for the monitoring of discharges.

As indicated, routine environmental monitoring will only be necessary for major practices such as nuclear fuel cycle facilities. Such facilities should also establish and maintain a capability for monitoring in the event of an emergency. In addition, other facilities that may not be subject to authorization may need to establish a monitoring capability for emergencies which may lead to environmental contamination. These include major metal recycling plants in which a dangerous source may inadvertently be melted.

2.3.2. Regulatory body

The responsibilities of the regulatory body relating to the control of discharges of radioactive material are set out in Refs [4, 9, 10]. In particular, the regulatory body is responsible for:

(a) Establishing, prompting or adopting appropriate regulations and guides upon which its regulatory actions are based in order to protect the public and the environment;
(b) Issuing authorizations for practices and setting the conditions to be attached to the authorizations;
(c) Defining and reviewing, at appropriate intervals, the technical requirements for monitoring arrangements;
(d) Ensuring, through inspection or otherwise, that the authorized person complies with the appropriate regulations and other requirements, for example, those specified in the authorization;
(e) Checking the monitoring data provided by the authorized person and, as considered necessary, undertaking or arranging for the undertaking of independent measurements to confirm the information that has been provided by the authorized person;
(f) Undertaking any enforcement action that is deemed necessary in the event of violations of the requirements.

The authorization procedure for new or modified facilities or activities includes consideration of dose constraints and the potential for release of radionuclides into the environment. The latter includes assessment of the inventory of radionuclides and the possible doses to members of the public, taking account of all the major release pathways and relevant site specific factors. Each facility has a characteristic spectrum of radionuclides that will be discharged. Based on this spectrum, the inventory and the assessed doses to the public, the regulatory body may limit the discharges of groups of radionuclides (noble gases, aerosol-bound radionuclides) and/or single radionuclides (e.g. tritium, carbon-14, iodine-131 and radon-222). Often the limits are expressed as annual limits but, depending on the circumstances, the regulatory body may also specify daily, weekly, monthly or quarterly limits. Its discharge limits for the key radionuclides are imposed as a condition of the authorization. The regulatory body also defines the requirements for the source and environmental monitoring to be carried out by the authorized person as a condition of the authorization. The final monitoring programme should be approved by the regulatory body.

Specifically with regard to monitoring, the regulatory body should:

(a) Establish the technical requirements for monitoring both discharges and uncontrolled releases of radioactive material;
(b) Check the monitoring data provided by authorized persons;
(c) Be able to provide evidence to demonstrate that the public is adequately protected.

IAEA Safety Standards Series No. RS-G-1.8 [10] notes that in situations where several sources may have an impact on the same areas and population groups, it may be difficult for the individual authorized persons to undertake environmental monitoring programmes to assess the cumulative radiological impact of these different sources, since they may not have information about the radionuclide composition of material discharged by other authorized persons. In such cases, the necessary monitoring may need to be arranged or carried out by the regulatory body.

The regulatory body is also responsible for ensuring that appropriate emergency arrangements are in place which are commensurate with any potential for uncontrolled releases of radioactive material to the environment [4, 5].

2.3.3. Other agencies

A number of other agencies may be given responsibilities by the government for environmental monitoring such as environmental monitoring programmes to:

(a) Confirm the data provided by the authorized person and to investigate environmental exposure pathways, to determine the cumulative radiological impact of single and multiple sources. In particular, further independent monitoring of discharges and/or the environment may be carried out on behalf of the regulatory body for purposes of check/compliance monitoring and public reassurance.
(b) Support the emergency response.
(c) Support remediation activities.

3. SOURCE MONITORING

3.1. OBJECTIVES

Source monitoring is defined as measurement of the activity in radioactive material being released to the environment or of direct radiation due to sources within a facility [1]. For the purposes of source monitoring, a facility is usually considered an aggregated source and source monitoring is focused on the points of releases to the environment (e.g. ventilation stacks, points of liquid releases) and dose and dose rates at the boundaries of the controlled, supervised areas and at the boundaries of the facility. Releases, whether as discharges or uncontrolled, can be in the form of gases, aerosols or liquids.

The specific objectives of a source monitoring programme within a practice, as defined in IAEA Safety Standards Series No. RS-G-1.8 [10], are to:

(a) Verify compliance with the authorized limits on discharges for airborne and liquid discharges;
(b) Provide the information necessary for checking if systems for waste treatment and control are performing properly;
(c) Provide early warning of any deviations from normal authorized operation;
(d) Provide data on the discharge of radionuclides to the environment, as a basis for the estimation by predictive modelling of environmental radiation levels and activity concentrations and exposure of the public (e.g. rates of discharge and radionuclide compositions).

These objectives are not listed in order of priority since the priorities will vary, depending on the circumstances that prevail at any given site. Their relative importance will also vary with the nature and amount of radionuclides that could potentially be released.

Additional information that may be obtained from a source monitoring programme, possibly in conjunction with environmental monitoring, includes:

(a) Identification of trends in discharges, especially those which may indicate a chronic plant or process problem;
(b) The relationship between the type of operations performed within the plant and the levels of radionuclides discharged;
(c) Dispersal and subsequent behaviour of radionuclides in different sectors of the environment that will assist in determining the environmental monitoring programme;
(d) Material that will assist in responding to the needs of stakeholders[7].

It is noted that a source monitoring programme provides data that can be incorporated into national and international[8] repositories of the records about the amount of radioactive material discharged to the environment.

[7] The term 'stakeholder' is not a well defined term but is used here loosely to mean interested or concerned parties. Such parties would need to be specified as relevant [1]. Examples of stakeholders are members of the public who might be exposed as a consequence of discharges from a particular plant.

[8] The IAEA supports the operation of the IAEA Member States' web based database DIRATA (http://dirata.iaea.org/), which is a worldwide centralized digital repository of Member States' records on discharges of radionuclides to the atmosphere and aquatic environment.

3.2. DESIGN OF SOURCE MONITORING PROGRAMMES

The source monitoring programme should be designed to give all the information needed to comply with the above objectives. In particular, in order to meet these objectives, a monitoring programme must be planned in advance. It should be such as to ensure that samples are representative and that sufficient data are available to determine total discharges over the relevant period given in the authorization and any trends over time.

Planning should define:

(a) The list of radionuclides to be included in the programme;
(b) The timing and frequency of sampling of the discharge;
(c) Where the samples are to be taken;
(d) Sampling methods to be used;
(e) The laboratory analysis programme;
(f) The manner in which the results should be recorded.

The radionuclide composition and activity concentration of discharges, particularly from nuclear facilities, may vary widely. Sampling programmes should therefore be chosen on the basis of a careful review of the anticipated radionuclide mixtures subject to the requirements specified by the regulatory body. They should be designed to cover at least those radionuclides that are important from a radiation protection point of view and, in every case, the specific radionuclides explicitly mentioned in the authorization granted by the regulatory body. In particular, source monitoring should focus on radionuclides that could lead to a significant fraction of the total dose to the representative person due to discharges. Where there is the possibility of other specific radionuclides being released in the event of an accident, some additional monitoring for those particular radionuclides should be considered.

In some cases, when this is permissible under the terms of the authorization, it may be sufficient to measure the gross activity, i.e. the total alpha or total beta/gamma activity of the discharge. This may be appropriate for noble gases, when the radionuclide composition of the discharge is sufficiently well known, or when the activity concentrations are low. When such measurements are undertaken, however, account may need to be taken of any naturally occurring radionuclides that may be present.

There are two general types of monitoring: continuous and discontinuous. In the case of discontinuous monitoring, the frequency of sampling and measurement is determined by the variability of the discharge rate and the likelihood of unplanned releases. These types of monitoring are discussed further in Section 3.3.2.

For all monitoring programmes, it is necessary to decide upon the location of the monitoring points. Where there is more than one waste stream, as might occur in a nuclear facility, it is important that each one in which radioactive contamination can be foreseen should be put under routine surveillance at the point of final discharge.

The monitoring points are chosen in such a way that the results of monitoring are representative of the actual discharges. Such points are generally situated downstream of the waste treatment systems for each waste stream discharging radiologically important radionuclides to the environment. Specific discharge points may be exempt from monitoring only if the extent of discharges and the likelihood of unplanned releases from them are trivial from the point of view of radiation protection.

The planning of the monitoring programme, and the finalized programme itself, should be fully documented and must be related to the overall management system. Management systems are the subject of IAEA Safety Standards and their application to source and environmental monitoring programmes is dealt with in Section 6.

The design of both the operator's and the independent compliance monitoring programmes should be periodically reviewed and updated in the light of the monitoring results and the assessments of doses to members of the public.

3.3. TYPES OF SOURCE MONITORING TECHNIQUES

Two main types of source monitoring are carried out:

(1) On-line monitoring of discharges (continuous sampling and measurement).
(2) Off-line monitoring of discharges either by:
    (i) Continuous sampling and laboratory measurements of activity concentrations in the sample;
    (ii) Intermittent or discontinuous sampling and laboratory measurements of activity concentrations in the sample.

3.3.1. On-line monitoring of discharges

On-line monitoring is taken to mean continuous measurement in real time or near real time (after a delay of no more than one hour). On-line monitoring systems provide a continuous indication to the operator of the quantity of radioactive material in the discharge. They are particularly useful in demonstrating that the treatment and control systems are performing properly and are usually provided where there is a potential for sudden and significant changes

in the level of radioactive material being discharged, especially where this could pose a potential off-site hazard. In many cases, they are used as warning systems and thereby enable rapid corrective action to be taken in the event of any deviation from the norm. At facilities with a significant potential for accidental releases, where possible, the results of continuous measurement should be transferred on-line to the licensee control centre or other appropriate operational centre. The alarm signal is immediately transferred to areas occupied by responsible personel (e.g. control rooms). Alarm or other reference levels, such as investigation levels, therefore, have to be defined for this purpose. The detection limits of on-line monitoring systems should be at least one order of magnitude lower than these levels.

On-line monitoring devices need continuous electric power supply. As these devices are important to ensure proper radiological protection of the population, it is important to make sure that no disruption of their functioning occurs and that, if it does, they can be repaired as soon as possible. At least a number of the continuous monitoring devices should be supplied, therefore, by an uninterruptible power supply. They also should be equipped with a warning device that indicates any instrument malfunction. The warning device should set off an alarm to a responsible person (e.g. in the facility operator technical team) who should trigger technical investigations and actions without delay.

Thus, the following thresholds may be considered for on-line monitoring devices (from the lowest to the highest values):

(a) One threshold well below the expected level, such a threshold serving to indicate instrument malfunction.
(b) One threshold just above the level which corresponds to the discharges in normal operation. Measurement results above this threshold would indicate an abnormal situation involving discharges which may require corrective action.
(c) One threshold corresponding to the authorized discharge limit or a fraction of this limit. If a discharge operation from a tank is in progress, the actuation of this threshold should automatically trigger the stopping of the current discharge. Note that such stopping is generally not possible for permanent airborne discharges for safety reasons and worker radiological protection considerations.
(d) One or several thresholds corresponding to safety considerations (detection of facility malfunctions).

Noble gases, total beta/gamma activity of aerosol-bound radionuclides and iodine-131 in discharges to atmosphere from nuclear facilities are often measured on-line. Indeed, since noble gases cannot be collected on filters, on-line

monitoring is generally necessary for the purposes of demonstration of compliance with the regulatory requirements. Aerosol-bound radionuclides and iodine isotopes, however, may be monitored by sampling and laboratory measurements.

The detailed technical requirements for the monitoring functions of centralized systems for continuous radiation monitoring of nuclear facilities are given in Refs [33–36]. Appropriate general information pertaining to on-line monitoring systems for liquid discharges can be found in Refs [37–39], and for on-line monitoring of discharges to the atmosphere in Ref. [40].

3.3.2. Off-line monitoring of discharges

Off-line monitoring involves sampling and subsequent laboratory measurement. The sampling may be continuous or intermittent and samples are usually processed remotely in the laboratory. Such procedures are usually necessary if radionuclide specific data or additional sensitivity are required. Off-line monitoring typically allows lower detection limits to be achieved for aerosol-bound radionuclides and iodine isotopes than by on-line monitoring. It provides a retrospective estimate of the discharges and is almost always used for accounting purposes to demonstrate compliance with authorization limits. Sampling is normally carried out by passing a representative sample of the discharge for a fixed period of time through a collection device. Laboratory measurements following continuous or intermittent sampling are considered in Section 6.

3.3.2.1. Continuous sampling

Continuous sampling and laboratory measurements are carried out to provide quantitative data on the annual releases of radionuclides and to demonstrate compliance with the authorized discharge limits. In particular, the laboratory measurements provide the opportunity for radionuclide specific data to be obtained. When the magnitude of annual releases is expected to be low, a two-step measurement procedure might be appropriate. As an initial analysis, the total alpha or beta activities could be measured. Radionuclide specific measurements would then only be carried out if the total activity exceeded defined levels for the total alpha or beta activities.

As with on-line monitoring, continuous sampling and measurement devices need continuous electric power supply and at least a number of the continuous sampling devices should be supplied, therefore, by an uninterruptible power supply. They also should be equipped with a warning device that indicates any instrument malfunction.

3.3.2.2. Discontinuous sampling

Discontinuous or intermittent sampling followed by laboratory measurement is usually appropriate for situations where the activity concentration of the discharge is expected to be very low and the release takes place at a relatively constant rate or where the release itself is discontinuous. An example of the former is the release of radon-222 (known simply as radon) to air from an underground repository, an underground mine or a mine tailings facility. An example of the latter is a liquid discharge released in batches.

Information regarding both continuous and discontinuous sampling of discharges to the atmosphere can be found in Refs [41–45], and for liquid effluents in Refs [46, 47].

3.4. AEROSOL AND GASEOUS DISCHARGES

The need for monitoring of releases to the atmosphere should have been taken into account in the design of the facility such that all gaseous and aerosol-bound radionuclides released from the facility can be monitored during routine operations and under accident conditions. All possible routes of release should have been considered.

In designing the actual monitoring programme for airborne discharges, the flow diagram of the ventilation and off-gas systems should be analysed in order to select the appropriate monitoring point. To permit the selection of satisfactory monitoring points and of sampling systems with suitable characteristics, the flow diagram should provide all the necessary information on flow rate, pressure differential, temperature, humidity, discharge velocity, etc.

The radioactive characteristics of the materials to be released and their variation with time must be taken into account in order to decide upon the most appropriate sampling and measurement rate and the extent of the additional information required.

The continuous measurement of air flow rate in the ventilation stacks is highly recommended. In many cases, monitoring of the radioactive substances in the discharge must be supplemented by the continuous or periodic measurement of some other relevant physical and chemical parameters which are necessary for the appropriate evaluation of the monitoring results, such as the temperature and humidity in the stack and in the sampling line, the chemical composition of the discharge, and the particle size distribution.

In order to calculate the total activity discharged to the atmosphere over a given time period from the measurements of activity concentration, it will be necessary to determine accurately the volume of material discharged as a function

of time. The total activity discharged can then be compared with any authorized limits imposed by the regulatory body. In order to calculate the radiation dose resulting from the discharges, relevant meteorological data and an appropriate assessment model will also be needed.

Any sampling system that is optimized for operation under normal conditions will also need to function adequately in the event of an abnormal occurrence.

The monitoring system must be calibrated regularly and its performance demonstrated against a reference standard.

The special features of stack monitoring for nuclear facilities are given in Appendix II and the technical details of the characterization of the size and biological solubility of radioactive aerosols are discussed in Appendix V.

3.4.1. Representative sampling

A representative sample of known air volume is necessary in order to determine the total amount of radioactive material discharged to the environment and the doses to the representative person. This is achieved by:

(a) Sampling from a suitable location;
(b) Sampling isokinetically and minimizing deposition in the sampling nozzle;
(c) Minimizing transport losses of the sampled material before collection.

These matters are discussed further in the following section. More detailed guidance on the monitoring of radioactive aerosols and representative sampling is available in Refs [48–50].

3.4.1.1. Selection of sampling location

The sampling points should in general be located downstream of any high efficiency particulate air (HEPA) filters, carbon absorbers and any other air cleaning equipment. They could also be located downstream of the exhaust fan to help ensure that the radionuclide discharge is well mixed at the sampling location. Ideally, the sampling point should also be where a stable flow regime has been established. If the exhaust air system comprises more than one discharge stack, monitoring of each stack usually is required. Although the intention is to select the most suitable location in order to obtain samples that are representative of the discharge, account will also need to be taken of the accessibility and feasibility of sampling.

The degree of mixing at the intended sampling position can be measured by using tracer gases. In systems having multiple exhaust streams that are combined

in a plenum, uniformity of flow is not a sufficient condition for a well mixed discharge. In such cases, the degree of uniformity of mixing can be measured using a non-reactive tracer gas (e.g. SF_6 or He). The tracer should be released at a constant rate into individual source ducts and the tracer profile measured in the cross-section of the exhaust duct at the proposed sampling location. Comparison of the profiles for the potential sources will show whether a single sample extraction point can be relied upon or whether multiple probes are necessary to ensure that a representative sample is obtained. A typical sampling arrangement is illustrated in Fig. 2.

3.4.1.2. Method of sample extraction

Usually the extracted sample is considered sufficiently representative if it is well mixed and comprises 0.01–0.001% of the total release or release rate to the environment. The sampling of aerosols should be undertaken using isokinetic sampling conditions at the point of sample withdrawal. This means that the velocity and direction through the sample nozzle is the same as the velocity and direction of the exhaust air at the point of withdrawal.

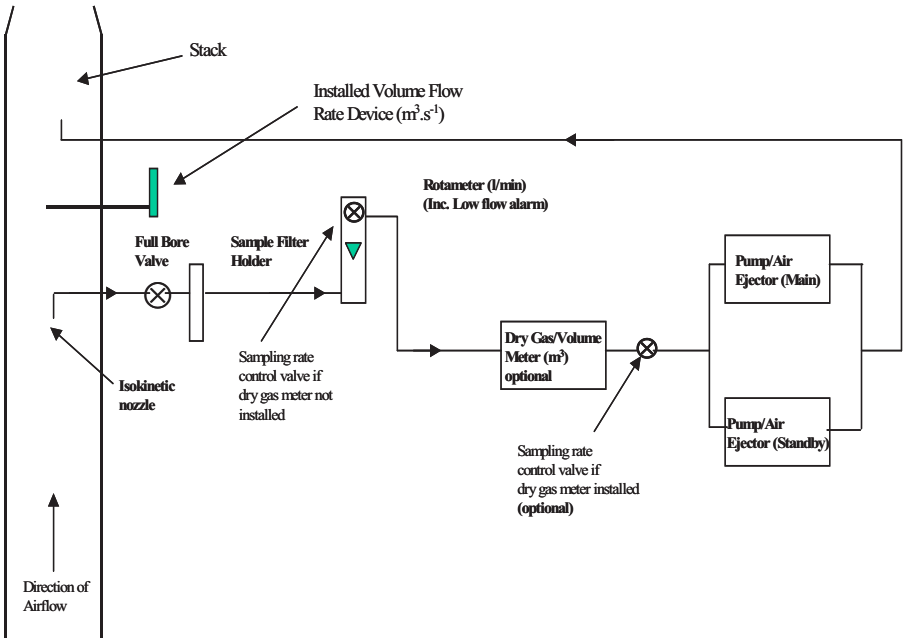

FIG. 2. Typical stack sampling arrangement.

The sampling nozzle should have a parallel bore and be tapered externally so that it presents a sharp edge to the incident flow. Any changes in internal cross-section should be gradual. The nozzle must be mounted so that it faces directly into the flow; however, small deviations are acceptable. The mounting arrangement must be downstream of the nozzle, so as to avoid any disturbance of the flow in the vicinity of the nozzle entrance. As discussed in Refs [49, 50], multiple nozzle arrangements may be warranted under certain duct arrangements to ensure representative sampling.

Isokinetic sampling, nozzle design and nozzle alignment requirements associated with the extraction of samples of aerosols are not important for sampling gaseous discharges. To obtain a representative sample, it is necessary only to ensure that the gas stream is well mixed and that the flow rates of both main and sample streams are known.

3.4.1.3. Sampling losses during transport

The sampling system should be designed so that the deposition of particles and isotopes of iodine during transport from the sampling nozzle to the collection filter is minimized and condensation of water vapour is prevented. In the sampling of aerosols, losses of particles may occur during transport from the sampling nozzle to the collection filter. The magnitude of these losses depends upon the particle size and density, as well as the parameters of the sampling system, such as line diameter, line length, flow rate, and number of bends and their radii. The losses result from deposition of particles on the walls of the line, because of gravitational settling, turbulent diffusion, and inertial impaction of particles at bends in the line [49, 51]. Generally, loss of larger particles (>10 μm) is mainly caused by bends, small duct diameters and diameter reductions in the sampling duct which should be kept to a minimum. Loss of smaller particles (<1 μm) is mainly caused by long sampling ducts and turbulent flow. The loss of particles of different sizes in transport is illustrated in Fig. 3.

Thus the length of the sampling line and the number of bends it contains should be kept to a minimum, and horizontal runs avoided, where possible. Flow rates and the diameter of the sampling line are chosen to avoid turbulent flow. Generally, this requires relatively large diameter sampling lines if a minimum bypass air flow rate of an adequate fraction of the total exhaust flow rate is to be realized.

Although the length of the sampling line should be minimized, other factors frequently determine the length and routing of such lines. It may be necessary to transport the sample some distance to ensure that the sampling point is sufficiently close to the release point and that the collection point is easily

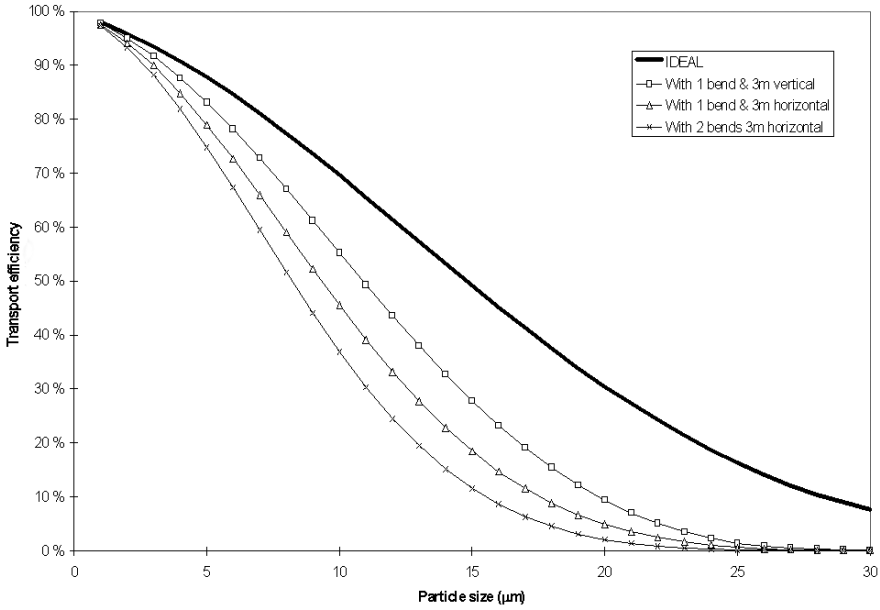

FIG. 3. The effect of transmission line geometry on sample transport losses.

accessible, even under emergency conditions. Such routing may also result in the introduction of several bends in the sampling line, although this problem may be minimized by thoughtful planning of the route to be followed and close supervision of the actual facility.

The choice of component materials is also important. Materials that have rough interior surfaces, or that react with or have a demonstrated affinity for the species being sampled, should be avoided. The choice of material is particularly relevant for iodine monitoring. Losses of iodine due to deposition in the sampling duct are greatest with metals, which should therefore be avoided, in particular for longer pipes. Materials with low deposition velocity are plastics (e.g. polyethylene), paints and Teflon.

Because some losses will inevitably occur during transport, it is necessary to provide a basis for correcting the measured concentrations to account for them. Losses in transport can be evaluated by semi-empirical formulas or by tracer studies with particles of known sizes [49, 52]. Losses of isotopes of iodine can also be evaluated from the deposition velocity of iodine on the inner surface material or by using tracer studies.

The condensation of water vapour can be avoided by heating the sampling line to ensure that, even in winter, the sample temperature does not fall to the dew

point during transport. A useful approach in this context is to keep the sampling duct within buildings or inside the stack.

3.4.2. Sample collection

Radioactive material may be discharged in several physical forms — as particulate, vapours or gases — and different collection methods are required for each of these forms. These methods are described in general terms in the following sections.

3.4.2.1. Particulate material

Aerosols are usually collected by drawing a sample of the discharge through a high efficiency filter paper (typically of glass fibre, but cellulose filters are also used). Impactors and electrostatic precipitators are also used [53]. The amount of radioactive material deposited on the filter is subsequently measured in the laboratory or, if an on-line measurement is required, a detector can be mounted above the filter. Selection of filters should be conducted such that the filter chosen is appropriate for any subsequent measurements [49]. Cellulose filters may not be suitable for gross alpha measurements due to penetration of the aerosol particles deep into the material of the filter. Glass fibre filters may not be amenable to dissolution as part of a radiochemical analysis and various types of membrane filters may suffer from clogging for higher sample volumes.

Filters are but one component of the sample collection system which also consists of the sample collector holder, an air moving device and a flow measurement device. The sample holder must provide structural support for the filter without damaging it or allowing the sample to bypass the filter. The air mover should be capable of providing constant flow over the filter without reduction due to progressive clogging. The sampler should be equipped with a calibrated air flow measurement device to allow for determination of the total volume of air passed and a measure of the uncertainty in the sample volume. Such data as flow rate and volume should be recorded. Information as to specific requirements for particulate material samplers can be found in Ref. [54].

3.4.2.2. Vapours

Radioactive material in the form of volatile vapours will pass through a filter paper or other collection device for particulate material, therefore, other forms of collection medium are required. Most vapours adsorb on to surfaces and trapping devices are designed to take advantage of this property. The most common material used is granulated activated charcoal. This material has a very

high surface area per unit mass (about 1000 m^2/g) and has a good removal efficiency for materials in vapour form. The basic characteristics of carbon and the mechanism of trapping vapours are described elsewhere [53]. Carbon is most commonly used for the collection of iodine, but it will also remove other elements such as sulphur, chlorine and noble gases. Combined particulate (filter paper) and activated carbon collection devices are typically used for sampling airborne discharges containing a mixture of radionuclides in different physical forms. Charcoal cartridges are prone to a number of factors that can reduce the efficiency of collection and are, therefore, often mounted in series.

3.4.2.3. Gases

The collection efficiency of activated charcoal for gases is variable; it depends on the specific chemical form of the element. Collection devices that are specific to the particular chemical form of the gaseous radioactive material under examination have therefore been developed. Two are mentioned here, namely, bubbler traps and scrubbers:

(a) Bubbler traps, as the name suggests, involve the passing of a sample of the discharge through a bottle containing a liquid that will absorb, either chemically or physically, the radionuclide of interest. An essential requirement is that there be good contact between the sample gas and the liquid, to ensure complete removal. Bubbler traps are widely used for sampling tritium in both elemental and tritiated water (oxide) (HTO) form.
(b) Wet scrubbers also operate on the basis of removal of the gaseous radioactive material from the discharge stream to a liquid collection medium. They consist typically of a glass cylinder filled with glass beads/tubing or other inert material. A recirculating flow of liquid passes down through the cylinder over the inert material while the gas to be sampled passes upwards. This arrangement maximizes the contact area and hence the mass transfer between the liquid and gaseous media. Water or a solution of a material that reacts with the radionuclide to be removed may be used. Periodically, the liquid is changed and the amount of radioactive material accumulated is determined. The method is primarily used in sampling for radioisotopes of ruthenium.

A third type of collection mechanism is cold traps, most often made of glass and comprise collection traps cooled to a temperature typically well below the freezing point of water. Such systems are used mainly for the collection of tritiated water vapour. Traps are most often found in series and two traps can typically exhibit collection efficiencies of over 99% for HTO [55].

Direct measurement is also used to monitor for gases when the chemical form of the radioactive material is such that it is not practicable to remove it from the discharge. This is particularly the case for radioisotopes of inert gases such as krypton and xenon. A sample of the discharge is drawn into a 'measurement chamber', which is of fixed calibrated dimensions and is at a controlled temperature. A detector then measures the activity in the chamber.

3.4.3. Monitoring and sampling of specific classes of radionuclides

This section deals in more detail with the various classes of radionuclides in airborne discharges. The following classes of radionuclides are identified:

(a) Noble gases;
(b) Aerosol (particulate)-bound radionuclides;
(c) Other gases and volatiles.

A listing of radionuclides likely to be encountered in the routine releases from a nuclear power plant is given in Appendix II.

3.4.3.1. Noble gases

Radioisotopes of argon, krypton and xenon need to be considered in the discharges from nuclear facilities. Radon-222 can dominate in releases from underground waste repositories, uranium mines, processing plants and tailings piles.

As indicated in the previous section, noble gases can be measured continuously by drawing a sample of the discharge through the measurement chamber. If the discharge is dominated by a specific radionuclide (such as argon-41 in the case of research reactors), a monitoring system capable of measuring the total activity in air (e.g. with a plastic scintillator or ionization chamber) is considered adequate.

For nuclear power plants where typically several radioisotopes of noble gases are discharged, analyses by high resolution gamma spectrometry with the use of high purity germanium (HPGe) detectors are necessary if data on the quantities of each radionuclide discharged are required, for example, for demonstration of compliance with authorized discharge limits. Where a total beta or gamma monitoring system is used, discontinuous sampling and measurement of noble gases by gamma spectrometry should be used to supplement the on-line measurements if radionuclide specific data are required. The frequency of such supplementary sampling would depend on the type of facility. As a point of principle, the samples should be analysed by HPGe gamma spectrometry as soon

as possible after extraction. However, if the detection of krypton-85 is difficult due to elevated activities of short lived radionuclides, for example, another measurement should be carried out two weeks after sampling to allow for their decay.

Simple beta counting systems and gamma spectrometers for use in routine situations may not be sufficient to meet the needs for monitoring in the event of an accidental release due to dead time losses at high count rates. Additional monitors may, therefore, be needed for the purpose of monitoring accidental releases.

In the case of underground uranium mines and uranium mills, measurements of radon-222 should be made in the exhaust air from the ventilation systems [56, 57]. Where the source is more widely distributed, as in the case of opencast mines and tailings piles, measurements of radon-222 should be undertaken [58] in such a way as to determine the total source term, depending on the requirements of the regulatory body.

Further information regarding the monitoring of noble gases can be found in Refs [59, 60].

3.4.3.2. Aerosol-bound radionuclides

For power reactors, aerosol-bound radionuclides are usually defined as those in particulate form with a physical half-life of more than eight days. They are usually grouped in three categories, according to their physical characteristics and, consequently, to the different measurement techniques:

(a) Beta/gamma emitters;
(b) Alpha emitters;
(c) Pure beta emitters.

The aerosol-bound beta/gamma emitters and alpha emitters that should be measured in the airborne discharges from nuclear power reactors are listed in Tables 7 and 8 in Appendix I. With respect to the dose to members of the public, the beta/gamma emitting radionuclides cobalt-60, ruthenium-106 and caesium-134/137, as well as the pure beta emitter strontium-90, are of special interest. The annual releases of alpha emitters such as plutonium are usually low and therefore of minor radiological concern.

The discharge of aerosols from research reactors is generally low and surveillance by total beta counting is usually considered sufficient. In order to reduce the influence of radioactive material of natural origin, primarily the decay products of radon-222 and radon-220 (its colloquial name is ‘thoron’), measurements are typically performed 24 h and 168 h after removal of the filter

from the monitoring position and compared with a guide radionuclide for the respective radionuclide group [61]. Generally, the most radiotoxic radionuclide is chosen as the guide radionuclide (e.g. yttrium-90 for the 24 h measurement, strontium-90 for the 168 h measurement). This avoids the need to undertake separate radionuclide analyses.

Radionuclides in the uranium (uranium-235 and uranium-238) decay chains are discharged in particulate form from uranium mining and milling, enrichment and uranium fuel fabrication plants. Transuranic radionuclides may be discharged when mixed (uranium and plutonium) oxide (MOX) fuel elements are fabricated. In all these cases, monitoring for the appropriate radionuclides should be considered.

The discharges from waste repositories have to be monitored during operation. The radionuclides to be considered may include the spectrum of all other facilities described previously. When the waste is stored for years before it is buried, the focus should be on radionuclides with half-lives of one year and longer.

Beta/gamma emitters

In order to demonstrate compliance with the authorized limits, the radioactive aerosols should be sampled using suitable filters. The filters should be changed at appropriate intervals and analysed by HPGe gamma spectrometry shortly after the end of the sampling period and/or measurement of the total beta activity after a set decay time.

In addition, on-line measurement of aerosols may be carried out. In this case, the release of radioactive aerosols should be sampled continuously using filters and the total beta activity on the filters measured continuously. If the accumulated activity exceeds a warning level, a signal should be initiated immediately and the sampling filters changed and analysed.

Alpha emitters

To provide data on the annual quantity released into the environment, alpha emitters should be sampled using suitable filters and analysed, at least quarterly. The filters should be changed frequently enough to avoid excessive dust loading. For practical reasons, it is generally sufficient to take one filter sample for both the beta/gamma and alpha analyses. After analysis by HPGe gamma spectrometry, the filter should be subdivided and further processed for measurements of specific radionuclides. The samples should be analysed after allowing for the decay of the short lived decay products of radon-222 and radon-220.

When the amount of alpha emitters released is expected to be low, for example, in nuclear fuel fabrication or enrichment plants, it is suggested that the total alpha activity be measured as a first step. This measurement is sufficient unless a predefined limit is exceeded, in which case the filters should be analysed for the specific alpha emitting nuclides.

On-line alpha monitoring should be considered for reprocessing plants and MOX fuel fabrication plants.

Aerosol-bound pure beta emitters

Strontium-90 is usually the only aerosol-bound pure beta emitter that needs to be routinely monitored in the discharges of nuclear facilities. The caesium-137 concentration is often used to trigger the analysis for strontium-90. Other radionuclides, such as iron-55 or nickel-63, might only be measured in special investigations to demonstrate that assumptions about the radionuclide spectrum are correct.

Strontium-90 is also sampled continuously on filters. For practical reasons, these filters might be the same type as those used for sampling the alpha and beta/gamma emitting radionuclides. Similar to the recommendation for alpha emitters, the samples should first be analysed by HPGe gamma spectrometry. Then, the filters should be subdivided and strontium-89/90 should be measured every three months in combined samples.

3.4.3.3. Other gases and volatiles

The only element whose isotopes are likely to be encountered routinely in this group in a nuclear power plant is iodine (mainly, the radioisotopes, iodine-131, iodine-132 and iodine-133). Iodine-129 is released principally from reprocessing plants and waste repositories. Tritium and carbon-14 are also important radionuclides in releases from heavy water reactors.

Iodine isotopes

Iodine isotopes may be released in three different forms: elemental, organic or attached to aerosols. Since the deposition velocity of elemental iodine is an order of magnitude greater than that of iodine attached to aerosols, and two orders of magnitude greater than that of organically bound iodine, it may be appropriate to distinguish between these three forms in source monitoring. However, this will only need to be considered where the doses from the different forms may be significant or where authorized limits are expressed for the different forms.

As a minimum, elemental and aerosol-bound iodine should be sampled. This is achieved by passing the sampled air first through a particulate filter to remove any iodine attached to aerosols, followed by an activated charcoal filter to remove the isotopes of iodine in elemental form. Generally, the sampling period should not exceed one week. An immediate measurement of iodine-131 after the end of the sampling period is preferable, but in any case, the delay before measurement should be short compared to the half-life. A decay correction for any delay is essential, as is a decay correction for the sampling period. For iodine-129, because of its long half-life, a delay is not important.

For power reactors, on-line measurement of iodine-131 might be appropriate, in order to provide early warning of any deviation from normal release levels. In this case, a sample of the discharge should be drawn through the sampling medium and the increase of the iodine activity with time should be monitored.

Total gaseous iodine (i.e. elemental and organic) can be successfully collected using specially packed beds or commercially available charcoal cartridges that have been impregnated with potassium iodide and/or triethylene diamine. Cartridges of silver loaded zeolite or alumina may also be used. Detailed information as to monitoring iodine isotopes in gaseous effluents can be found in Ref. [62].

Tritium

Where tritium releases are or could be significant with respect to the authorized limits, tritium should be sampled. Tritium is a significant radionuclide in releases from heavy water reactors and reprocessing plants. The release of tritium from other facilities, such as fuel fabrication plants, is very low and monitoring is not required.

Tritium should be collected in the form of HTO vapour. Any tritium released as molecular tritium (HT) or in any organic form (e.g. hydrocarbon) should be oxidized to HTO by passing the sample stream over a heated catalyst. The sampling of tritium should normally be continuous, but the period over which the measurement is made could vary from a week to three months. The lower the release rate, the longer the sampling period could be. The sampling medium is usually a liquid such as water, but aqueous solutions of, for example, sodium hydroxide may also be appropriate, particularly when sampling carbon-14 simultaneously. Adsorption with molecular sieves or silica gel and condensation of atmospheric moisture have also been used to sample tritium. In the case of molecular sieves, care should be taken that no other trapped radionuclides interfere with the measurement.

For atmospheric discharges such as water vapour from cooling ponds, cooling towers and from open pool type reactors, a practical approach is to measure the tritium content in the water and estimate the tritium release using the evaporation rate (or resultant elevated humidity in ambient air) from the cooling pond, tower or pool water surface. An alternative approach may involve the measurement of tritium in atmospheric water vapour. Further information regarding the monitoring of tritium can be found in Refs [63–67].

Carbon-14

Due to its low and constant rate of release from most reactors, continuous monitoring of carbon-14 may not be necessary. It would be sufficient to monitor the release of this radionuclide once in the lifetime of the facility or to use data from comparable facilities. It is relevant, however, for reprocessing plants. In waste incineration plants or carbon-14 labelling facilities, routine monitoring may be necessary.

If the measurement of carbon-14 is considered relevant to the facility, it should be collected in the form of carbon dioxide gas. As for tritium, any organically bound carbon or carbon monoxide should be oxidized by passing the sample stream over a heated catalyst. Sampling should normally be continuous, but the period over which measurement is made could vary from a week for a reprocessing plant to three months for other facilities. The sampling medium is usually an aqueous solution of sodium hydroxide, from which the carbon is precipitated later in the laboratory in the form of barium carbonate and analysed by liquid scintillation counting. Use of barium hydroxide instead of sodium hydroxide as the sampling medium would allow the barium carbonate to be precipitated directly, and this may be the preferred approach. The carbon dioxide can then be released by acidifying the hydroxide solution and collecting it in an alkylamine solution, and the carbon-14 determined using a liquid scintillation counter.

Depending on the power level and the construction features of accelerators, monitoring of short lived gaseous activation products (e.g. oxygen-18, fluorine-18) may be required.

3.5. LIQUID DISCHARGES

Discharge water that may contain radioactive material should only be released through authorized routes [2]. It is normal practice to collect discharge water in storage tanks, but it may be acceptable to release it directly into the environment, if the radionuclide concentration gives rise to only very low doses

to members of the public. Collected discharge water after any necessary treatment and delay to allow for radioactive decay is discharged on a discontinuous (batch) basis.

Several requirements of the monitoring programmes for radioactive liquid discharges are, in principle, similar to those of the monitoring programmes for airborne discharges, and the same general principles have to be applied when establishing an adequate programme. It is necessary as a first step, therefore, to analyse the flow diagram of liquid discharges in order to define the appropriate monitoring points in the network of tanks and discharge lines.

The characteristics of the materials to be released (radionuclide content, physicochemical form, etc.) and their variation with time must be taken into account in order to decide upon the most appropriate sampling and measurement regime, and the parameters that need to be measured.

The discharge of any liquid should be carried out only under appropriate control which ensures that the authorized discharge limit will not be exceeded. This requires that each batch be subjected to appropriate monitoring procedures, which include the taking of a representative sample and the measurement of its radioactivity content before discharge, so that a comparison can be made with the discharge limits established by the regulatory body. Continuous measurement of the actual discharge of a batch, with provision for automatic termination of the discharge, may also be appropriate to prevent abnormal releases.

The radionuclide concentration should be measured in all discharge water released to the environment. In order to calculate the total activity discharged over a given time period, it will be necessary to determine accurately the volume of water discharged as a function of time. This can then be compared with any authorized limits imposed by the regulatory body. In order to calculate the radiation dose to the representative person resulting from the discharges, information on the environmental pathways leading to exposure and an appropriate assessment model will also be needed.

The type of measurement required will depend on the way in which the discharge limit is specified and on the anticipated nature and amounts of radionuclides to be discharged. If the discharge limit is given in the form of a discharge formula relating to the activities of a number of specified radionuclides, the measurement should determine the activities of the radionuclides explicitly mentioned in the discharge formula.

If a specific radionuclide analysis cannot, for technical reasons, be obtained in due time, at least a gross activity measurement should be made on each batch before discharge. Where samples of the batch release have been taken before discharge, for gross activity measurement, the measurement of the specific radionuclides can be performed at a later stage for reporting purposes.

Since the chemical nature of the mixture of liquid discharges in the batch may vary and the suspended matter present may cause enrichment and sedimentation effects, particular attention must be given to ensuring the homogeneity of the sample, in order to achieve adequate representativeness.

In the case of large discharges of radioactive liquid to a receiving body of water, the regulatory body may require a final monitoring point downstream of all possible discharge pathways, for example, in the water outlet system just before the mixing of the liquid discharge with the receiving water body. Continuous collection of samples proportional to the volume discharged should take place at this point, followed by periodic laboratory analysis of the radionuclide composition of the samples. Continuous sampling would not be necessary, however, where the discharges give rise to only very low doses to members of the public.

If there is a significant potential for an unplanned release, as might be the case with a nuclear facility, the continuous sampling in the discharge line should be supplemented by continuous direct measurement and the triggering of an alarm if the measurement exceeds a predefined level.

As with airborne discharges, the monitoring system must be regularly calibrated and its performance demonstrated against a reference standard.

Appropriate further information on monitoring of radioactive discharges to water from nuclear facilities can be found in Refs [46, 47, 68, 69].

3.5.1. Sampling principles for discontinuous releases

Discharge limits established by the regulatory body should take into account:

(a) Impact of the radionuclides released, particularly the doses to the representative person;
(b) Flow rate of released water relative to the flow rate of the receiving medium (river, creek);
(c) Volume of discharged liquid relative to the volume of the receiving medium (lake);
(d) Nature of the receiving environment.

These discharge limits will generally relate to the amount of radioactive material that can be released over a period of time and activity concentrations for the discharge of a given batch of radioactive discharge water would need to be

derived from them[9]. Before the release of a batch of stored discharge water, a representative sample should be taken. For this purpose, the contents of the tank should be thoroughly homogenized. The representative sample then is evaporated and the residue is measured for comparison with the derived activity concentration.

To assist in quick decision making with regard to the release of a batch of liquid discharge, sometimes (if homogeneity and geometry permit) a simple measurement of the gamma radiation dose rate in the storage tank may be made and may be compared with a predefined level that will ensure compliance with the authorized limit. In this case, the predefined level should take account of such factors as the efficiency of the monitoring system for the different energies of the gamma rays that are emitted by the radionuclides that might be present. Even if this approach is used, a representative sample of the material released should be obtained for subsequent measurement. This approach is only acceptable, however, if it is clear that short lived radionuclides are not present in the discharge water.

3.5.2. Sampling principles for continuous releases

As already indicated, the most frequent practice is to discharge liquid radioactive discharge in batches. However, if the discharges give rise to only very low doses to members of the public and where concentrations of radionuclides are considered unlikely to vary significantly, it may be acceptable to release directly to the environment on a continuous basis and without further treatment. The discharges should be sampled, however, unless the discharge has been exempted from the regulatory requirement of authorization, and monitored either continuously or at intervals, in order to determine the amount of radioactive material released. A commonly used approach for sampling a continuous discharge is to bleed off a proportional sample (e.g. 0.001%) of the discharged water continuously into a container, the content of which is then changed and measured at given intervals. Limits should be set for the results of these measurements. These limits should be based on the authorized limits issued by the regulatory body.

[9] The term ‘derived limit’ is often used in this context. It means “a limit on a measurable quantity set, on the basis of a model, such that compliance with the derived limit may be assumed to ensure compliance with the primary limit” [1]. Sometimes the term ‘derived level’ is used with a similar but more general meaning.

3.5.3. Measurements to provide data on quantities of discharged radionuclides

Authorized limits issued by the regulatory body are generally specified in terms of total activity of defined radionuclides (or in some cases, the total beta or alpha activity) that may be discharged during a particular time period. As such, either: (a) the results of monitoring should be capable of being integrated over the particular time period so that a comparison can be made with the authorized limits; or (b) levels that can be directly compared with the monitoring results should be derived from the authorized limits such that, if the results remain consistently below these levels, there is virtual certainty of compliance with the authorized limits.

Clearly, measurement of each radionuclide specified in the authorization will enable a direct comparison to be made with the authorized limits or the levels derived from them for the particular measurement method used.

The measurement approach can be simplified in some cases by measurement of the total beta and, if necessary, the total alpha activity concentration of the radionuclides in the discharge water. Where this is done, it would be sufficient to assume that all of the measured activity was due to the most toxic alpha or beta emitting radionuclide defined in the authorization. This approach would need to take account of the activity concentration of potassium-40 (in the case of the measurement of gross beta activity concentration) that is naturally present in the discharged water. The activity concentration of potassium-40 in the ocean and in freshwater could be in the range of 9–12 Bq/kg and 1–30 Bq/kg, respectively.

If the results of this simplified method are consistently below the level for the most toxic radionuclide, then this should indicate virtual certainty of compliance with the authorized limits. However, if this is not the case, then measurement of each radionuclide would need to be made, by HPGe gamma spectrometry or chemical separation of the specific radionuclides, as appropriate.

In general, the radionuclides to be measured and the frequency of measurements will depend on the type of facility and its potential or actual impact.

3.5.4. Sampling requirements

Liquid discharges are monitored primarily for the purposes of demonstrating compliance with the authorized limits. When samples are collected, they should be representative of the discharged water being sampled. This is especially important if suspended solids, as well as dissolved species, are present. The discharge water should be thoroughly mixed before sampling and

the flow velocity in the sampling line should be high enough to keep the sample well mixed. If the contents of the tank containing the discharge water cannot be mixed, sampling should be performed at the inlet to the tank, while the tank is being filled, or at the outlet, while it is being emptied. The proportion of the discharge water which should be sampled depends on the volume of the discharge and the volume of the sample that can be conveniently collected and analysed. From the moment of sampling until the end of the discharge procedure, no additional water should be released into the tank. The total amount of radioactive material discharged can then be obtained from the measurement of the activity concentration of the sample and the total volume of the liquid to be discharged.

If a potential exists for unplanned releases of discharge water, for example, when small discharge water storage tanks are used and there is the possibility of overflow, a sample of the discharge water being released should be drawn off continuously for subsequent measurement, if necessary. A gamma monitor may be required which automatically stops the discharge if a preset gamma activity is exceeded or if the monitor fails. If this occurs, an alarm should be triggered in the operator's control room or other appropriate operations area.

The authorized person should, as required by the regulatory body, retain aliquots of all samples or all radioactive material prepared for measurement, for a period defined by the regulatory body. It is recommended that this period be at least one year.

3.6. DIRECT RADIATION

The measurement of direct radiation from the source is an essential requirement of the source monitoring programme for most types of nuclear facility. Dose and/or dose rates should usually be measured at the boundaries of the controlled, supervised areas and at the boundaries of the facility. Such systems have the potential to measure the gamma radiation associated with the release of radioactive material.

A common method for monitoring the direct gamma radiation from the source is through the use of on-line dose rate meters [70–76]. These should be used where there is the possibility of an unplanned significant increase of the direct radiation from the source or unplanned release of radioactive material. For large facilities, the on-site network of on-line dose rate meters is often a part of the on-line environmental monitoring and alarm system located around the facility. The environmental part of such a network can be placed on several circles of increasing diameter (e.g. 1 km, 5 km and 10 km) or close to villages or cities. It is recommended that they should be placed close to any air or rainwater samplers used for environmental monitoring purposes. Further details about

environmental monitoring of external radiation are provided in Sections 4.4.1 and 5.2.1.

Alternative or supplementary methods may include the use of off-line integrating passive devices, such as solid state dosimeters [77, 78] (e.g. thermoluminescent dosimeters (TLDs)) or a combination of on-line and off-line methods. The number of dosimeters to be used should be dependent on the type and the size of the facility, and the distance to the fence line. They should be regularly distributed at the fence around the facility, at the place where the dose is expected to be the highest, as well as close to the potential location of the representative person. If radioactive waste is stored near the fence, one or several dosimeters should be placed at the fence close to the waste storage facility. Dosimeters should also be placed at the fence close to the parking area for fuel transport vehicles. They should be placed about 1 m above the ground in areas not shielded by buildings. A typical integration time is 1–6 months.

The dose rates from neutrons might be significant around some plants where high level waste or irradiated fuel elements are present, such as reprocessing plants, interim storage facilities or repositories. Dose rates should also be measured around these facilities. In these cases, integrating neutron dosimeters should be distributed again along the boundary [79]. Depending on the size of the facility to be monitored, 6–12 dosimeters distributed around the facility would normally be sufficient. Under normal conditions, the dosimeters should be changed every six months. In the case of an accident, the dosimeters should be evaluated immediately.

All dosimeters should be calibrated. Particular care has to be taken in the calibration of the dosimeters used for the measurement of neutron radiation, because both the relative detection efficiency and the fluence-to-dose conversion factors are strongly dependent on the energy of the neutrons.

3.7. SYSTEM OPERABILITY

The regulatory body should consider if the registrant and licensee should provide some or all of the following functions for the sampling/monitoring systems used for measuring the discharges of radioactive material to the environment:

(a) An alarm to be triggered in the event of a significant drop in the flow rate through the sampling system;
(b) An alarm to be triggered in the event of a significant drop in the pressure across the filter, which might indicate that the filter has been breached;

(c) An alternative means of sampling the discharge with either a manual or automatic switchover in the event of failure of normal extraction system;
(d) A standby power supply.

The decision regarding whether these are necessary should be based on the significance of the discharges in terms of the dose to the representative person and the potential for significant unplanned releases.

3.8. CALIBRATION, OPERATIONAL CONTROL AND MAINTENANCE OF THE SYSTEMS

Calibration of installed measuring equipment, such as on-line gamma monitors and flow meters, should be undertaken regularly.

The status of the on-line monitor should be given in the control room of the plant or other appropriate operational area. In particular, an alarm should be given in the event of an unusually high level of activity in the discharge or failure of the monitor.

Comprehensive functional checks of the monitoring system should be carried out by the authorized person in accordance with a schedule agreed with the regulatory body. The preset alarm levels and their operability to produce an appropriate alarm when a defined level has been exceeded should be checked at regular intervals as described in the maintenance protocol.

The authorized person should establish and undertake a routine maintenance schedule for the sampling and measurement systems. There should be a prescribed response time for dealing with any breakdown. Appropriate spares should be available so that repairs can be carried out in a timely manner. The sampling system should be checked periodically for any leaks and blockages. If the discharge contains suspended solids, it may be necessary to flush the sample lines from time to time to remove any accumulated solids.

Records of maintenance activities should be kept for external verification for a period that has been agreed by the regulatory body.

3.9. VERIFICATION OF THE OPERATOR'S MONITORING SYSTEM AND MEASUREMENT PROGRAMME

The complete set-up and strategy of the source monitoring system should be approved by the regulatory body. This comprises:

(a) Monitoring of the radionuclides or classes of radionuclides;
(b) Design of the sample extraction and collection system, including the position of sample extraction, sampling duct, filter type, etc.;
(c) Required measuring range of the monitoring system (including emergency monitoring, if required);
(d) Documentation of measurement results;
(e) Time period over which this documentation should be kept.

As already indicated, source monitoring is the responsibility of the authorized person. However, verification of the source monitoring programme undertaken by the authorized person should be carried out by an independent accredited measuring laboratory or other body on behalf of the regulatory body. The verification should cover:

(a) Calibration of the monitoring systems;
(b) Periodic surveillance of the measurements undertaken by the authorized person during operation.

The laboratory of the authorized person should be accredited to do the measurements by a recognized accreditation body.

While the authorized person should calibrate the total monitoring system including the system to measure the volume of exhausted air or discharged water and, in the case of discharges to atmosphere, the wind speed and other atmospheric parameters, the independent measuring laboratory should verify the calibration and the quality of the measurements.

For on-line monitoring, verification of the calibration of the monitoring equipment might be done by the verifying laboratory installing its own measuring system in parallel so that the measurements may be compared. The calibration measurements should be repeated at least every three years for on-line monitoring systems. The on-line monitoring systems should be calibrated with appropriate standards. For example, xenon-133 and krypton-85 could be used for calibrating noble gas monitors. The monitoring systems for aerosols could be calibrated with strontium-90/yttrium-90 for beta emitters, with cobalt-60 or caesium-137 for gamma emitters, and with americium-241 for alpha emitters. If radioisotopes of iodine are monitored on-line, the system could be calibrated with iodine-131.

The independent measuring laboratory must be able to verify all measurements carried out by the authorized person. The authorized person should provide, therefore, the independent laboratory with samples or aliquots of samples. It is recommended that the independent measuring laboratory should measure 1–10% of all the samples taken by the authorized person. If experience in the first year demonstrates that the quality of the measurements made by the

authorized person is adequate, the number of independent analyses can be decreased.

Ideally, the samples should be transferred to the independent laboratory in their original form. However, in some cases, it might be necessary for the authorized person to prepare samples (e.g. to dissolve filters). In these cases, the authorized person must ensure that the total activity has not changed during preparation.

Periodic intercomparison exercises nationally or internationally should be considered, if feasible.

3.10. PECULIARITIES OF SOURCE MONITORING FOR REGISTERED FACILITIES

Since the inventory of radionuclides in registered facilities[10] is usually low and, therefore, the potential for accidental releases is very low or non-existent, the objectives of the registrant's (authorized person's) monitoring programme are simply to provide data on the quantity of radionuclides released, to demonstrate compliance with the discharge limits. In the case of hospitals practising nuclear medicine, the discharges can often be estimated from the amounts of radionuclides administered to patients. Examples of where this can be done are given in the following sections.

3.10.1. Airborne releases

Xenon-133 and other gases are used in nuclear medicine for diagnostic purposes. Special monitoring of the discharge is usually not necessary, since the total activity discharged can be calculated from the activities of the radionuclides administered to patients over the relevant time period. In such cases, all that will be necessary will be for the calculations to demonstrate that the authorized limits for the relevant time period have not been exceeded. A similar approach might be used in small research laboratories using limited amounts of radionuclides, for example, for tracer studies.

For some facilities where more elevated or significant discharges could occur, continuous and/or discontinuous sampling and measurement are usually sufficient. For example, on-line monitoring might be appropriate when there is the possibility of temporarily enhanced releases, especially of iodine-131. In such cases, it might be useful to combine on-line measurement with continuous

[10] See footnote 1.

sampling. Radionuclides are sampled continuously and measured during accumulation on the filter or other medium. Total beta or gamma measurements are usually sufficient to show compliance with authorized limits. After the sampling period, the filter can be analysed in the laboratory to provide more accurate data on the total quantity discharged.

3.10.2. Liquid releases

The monitoring system for liquid releases should be the same as in licensed facilities. The discharge water should be collected in tanks and sampled. Before discharge into the environment, a representative sample must be taken and the relevant radionuclides measured. The sampling techniques and the measurements correspond with the recommendations for licensed facilities.

When only short lived radionuclides are present in the discharge water, it might be sufficient to demonstrate by decay calculations that the radioactivity in a tank will not exceed the authorized discharge limits.

3.10.3. Direct radiation from the source

Continuous measurement of the gamma dose rate in the vicinity of registered facilities is not normally necessary. In many cases, it would be sufficient to undertake occasional surveys to determine that the situation remains satisfactory. However, integrating measurements of gamma dose rates around registered facilities should be considered where some sealed sources, radiation generators and accelerators are used.

4. ENVIRONMENTAL MONITORING

4.1. OBJECTIVES

Environmental monitoring is defined as the measurement of external dose rates due to sources in the environment or of radionuclide concentrations in environmental media [1]. Environmental monitoring systems are complementary to source monitoring systems. They can be divided into two types: source related and person related environmental monitoring [10]. The primary purpose is to provide information to ensure proper protection of the population.

The specific objectives of environmental monitoring as given in IAEA Safety Standards Series No. RS-G-1.8 [10] are to:

(a) Verify the results of source monitoring and the associated modelling, to ensure that the predictions are consistent and that exposure limits are not exceeded;
(b) Check environmental radiation conditions for compliance with the authorized environmental limits, if applicable;
(c) Provide information to enable the assessment of actual or prospective doses to the representative person resulting from authorized practices or sources;
(d) Detect any unpredicted changes in activity concentrations and to evaluate long term trends in environmental radiation levels as a result of the discharge practice;
(e) Provide information to the public.

In particular, environmental monitoring provides a more direct assessment of the levels of contamination due to releases of radionuclides from facilities to which members of the public are exposed than does source monitoring.

Paragraph (d) should be interpreted as covering unplanned releases of radioactive material to the environment. Thus, an important objective of environmental monitoring programmes is that equipment be available for use in an emergency situation and that staff be trained in using the equipment. In addition, the routine monitoring programme will provide information on the levels of radionuclides normally in the environment against which measurements made during an emergency can be compared. It will also be necessary to establish levels above which investigations should be carried out to determine whether an unplanned release has occurred.

Additional reasons for undertaking an environmental monitoring programme may include the need:

(a) To assess the cumulative environmental impact of several or diffuse sources of radioactive material;
(b) For investigations into the movement of radioactive material through the environment, for example, in order to establish a routine environmental monitoring programme.

It has long been assumed that if humans are appropriately protected, then the environment in general will also be [80]. However, this has not been unequivocally demonstrated and, as a consequence, further consideration is being given to the matter. In particular, the ICRP, in order to provide a sound framework for environmental protection in all exposure situations, proposes the use of

'reference animals and plants' [30] as a tool for prospective assessments although not intended for the design of monitoring programmes.

Discussion of environmental monitoring programmes within the context of protection of non-human biota is beyond the scope of this report.

4.2. DESIGN OF MONITORING PROGRAMMES

The design of an environmental monitoring programme should be consistent with the objectives of monitoring. The need for and scale of an environmental monitoring programme will be determined primarily by the significance of the expected doses to the representative person and based on the requirements specified by the regulatory body in the authorization for the discharge from the particular practice. In particular, the environmental monitoring programme should be designed such that the radionuclides that are significant in terms of dose to the representative person are monitored.

Since environmental monitoring is complementary to source monitoring — they are both concerned with the protection of the public — the environmental monitoring programme should be developed so that it harmonizes with the source monitoring programme.

The frequency of monitoring and sampling should be determined by the complexity of the environment, the significance of the doses to the representative person and the properties of the radionuclides. For example, if short lived radionuclides (e.g. iodine-131) are to be monitored, the frequency of monitoring should be sufficient to detect them.

The environmental monitoring programme should also include pre-operational monitoring of the background levels so that the incremental contribution from the practice can be determined. This is particularly important with practices that discharge NORM.

It is the responsibility of the registrant or licensee to establish and implement the environmental monitoring programme, subject to review by the regulatory body, for planned exposure situations. In case of emergency or existing exposure situations, other agencies or authorities may be designated to conduct environmental monitoring [2]. As with source monitoring, further independent monitoring, in this case, of the environment, may be carried out by an independent organization on behalf of the regulatory body for the purpose of verification and public reassurance. In addition, the regulatory body may wish such independent monitoring to include more detailed studies of exposure pathways.

Measurements in the environment should be concentrated on external radiation dose rates and concentrations of radionuclides in environmental media. The environmental media that should be monitored are those that are relevant to the pathways of exposure of members of the public and those that are used as indicators of the contamination of the environment resulting from the authorized discharge.

The pathways of exposure that should be considered in the design of an environmental monitoring programme are:

(a) External radiation from radionuclides in the air and deposited on the ground or in sediments;
(b) Inhalation of radioactive material in the air and absorption of radionuclides through the skin[11] resulting directly from the release or through resuspension of material deposited on the ground;
(c) Ingestion of foodstuffs and other environmental material contaminated by radionuclides.

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.

In addition, relevant cultural, socioeconomic and demographic factors of the local population should be considered.

Environmental monitoring programmes related to different facilities are discussed in Appendix I.

Recommendations regarding the monitored constituents and the frequencies of sampling and measurement for discharges of radionuclides to the environment are given in Table 2.

[11] The absorption of radionuclides through intact skin could be important with just a few radionuclides. For example, for a sedentary adult male absorption of HTO through intact skin contributes approximately one third of total HTO intake for a given atmospheric concentration and should be considered additionally in dose assessments because it is not included in the derivation of the inhalation dose coefficients published by the ICRP and the IAEA [2].

TABLE 2. ENVIRONMENTALLY MONITORED CONSTITUENTS AND SUGGESTED FREQUENCIES OF SAMPLING AND MEASUREMENT FOR DISCHARGES OF RADIONUCLIDES TO THE ENVIRONMENT
(modified from Ref. [10])

Discharge	Monitored constituents	Frequency
Airborne	External radiation	
	Gamma dose rate	Continuously
	Gamma dose integrated	Twice a year
	Neutron dose rate (if neutron radiation is foreseen)	Continuously
	Neutron integrated rate (if neutron radiation is foreseen)	Twice a year
	Air, deposition	
	Air	Continuous collection, weekly to monthly measurement
	Precipitation	Continuous collection, monthly measurement
	Deposition	Continuous collection, monthly measurement
	Soil	Once a year
	Foodstuff and/or ingestion	
	Leafy vegetables	Each month during growing season
	Other vegetables and fruits	Selected samples, at harvest
	Grain	Selected samples, at harvest
	Milk	Each month when cows are on pasture
	Meat	Selected samples, twice a year
	Drinking water and/or groundwater	Twice a year
	Terrestrial indicators	
	Grass	Each month when cattle are on pasture
	Lichen, mosses, fungi as appropriate	Selected samples, once a year

TABLE 2. ENVIRONMENTALLY MONITORED CONSTITUENTS AND SUGGESTED FREQUENCIES OF SAMPLING AND MEASUREMENT FOR DISCHARGES OF RADIONUCLIDES TO THE ENVIRONMENT
(modified from Ref. [10]) (cont.)

Discharge	Monitored constituents	Frequency
Liquid	Water bodies	
	Aquatic species	As appropriate
	Surface water	Continuous sampling, monthly measurement
	Sediment	Once a year

Although environmental monitoring programmes are primarily developed for the purpose of controlling the exposure of members of the public to discharges, they should also take account of the need to rapidly detect any abnormal situation so that an appropriate response can be made.

The design of the environmental monitoring programme and of any separate environmental monitoring programme established by the regulatory body for confirmatory purposes should be periodically reviewed and updated in the light of the monitoring results and assessments of the associated doses.

Recommendations on measurement of radionuclides in food and the environment, including recommendations about laboratories, equipment and personnel, collection and preparation of environmental samples and analytical methods, are provided at Ref. [81]. Other comprehensive guides and compilations of methods and procedures include Refs [82–84] and best practice techniques for environmental radiological monitoring are described in Ref. [85]. Appropriate information about monitoring of indicator materials can be found in Refs [86–94].

4.2.1. Pre-operational studies

As indicated in IAEA Safety Standards Series No. RS-G-1.8 [10], pre-operational studies, which may include both monitoring and collection of available statistical data, should be carried out by an appropriate responsible body (e.g. design organization, registrant, licensee) for practices, to establish the baseline or existing environmental radiation levels and activity concentrations for the purpose of determining the subsequent impacts of the discharges. This is particularly necessary for nuclear facilities but also should be considered for other practices that might discharge significant quantities of radionuclides to the

environment, such as some mines producing and industries handling NORM. Such studies would not, however, appear necessary with, for example, hospitals discharging short lived radionuclides from the practice of nuclear medicine, or research establishments discharging only small quantities of radionuclides.

The pre-operational monitoring programme should take account of the types and amounts of radionuclides that might be discharged during the operation of the facility, and the possible exposure pathways. It should be such as to provide basic environmental data for use in the prediction of doses to the public. The pre-operational studies should generate statistically appropriate baseline data of relevance to any subsequent environmental monitoring programme. The authorized discharge limits and the conditions of discharge to the environment should be established and the environmental monitoring programme designed with due account being taken of these pre-operational studies.

The pre-operational monitoring programme should, in general, be implemented at least one year before a facility goes into operation, in order to determine the existing background and natural variations.

4.2.2. Routine monitoring

Environmental monitoring should be carried out routinely throughout the operational period of the facility.

As indicated previously, the environmental monitoring programme should be reviewed periodically to determine that it is adequately meeting the required objectives. The frequency of such reviews will depend on such factors as:

(a) Significance of the releases in terms of the consequential doses to members of the public;
(b) Potential for changes in the level of releases to the environment or exposure to direct radiation;
(c) Requirements imposed by the regulatory body;
(d) Experience gained in undertaking the monitoring programme;
(e) Any changes in practice, such as the use of the land around the facility, that might significantly alter the initial assessment on which the authorization to discharge radioactive material was based.

In general, however, the frequency of the reviews of environmental monitoring programmes for nuclear facilities, including uranium mines and mills, would be of the order of a year or so. In some cases, the review might indicate that the programme can be reduced. Changes of land use in the vicinity of the facility, however, might force a revision of the programme.

The monitoring programme should reflect the operational stage of the facility (operation, decommissioning, post-closure) and continue as long as releases or exposure to direct radiation might occur. Some measurements (e.g. of short lived radionuclides) may be stopped immediately after shutdown.

4.2.3. Investigative monitoring

In the event of an abnormal release of radioactive material from the facility, additional environmental monitoring may be necessary. This is dealt with in Section 5, which covers monitoring during and after an accidental release.

4.3. MONITORING OF AIR AND RADIONUCLIDE DEPOSITION

Radionuclides discharged to the atmosphere can lead to exposure of members of the public from:

(a) External radiation from the passing plume;
(b) External radiation from deposited radionuclides;
(c) Inhalation of radionuclides in the plume and resuspended from the ground;
(d) Ingestion of deposited radionuclides in foodstuffs and water;
(e) Absorption of radionuclides through the skin.

In establishing environmental monitoring programmes for normal airborne discharges, consideration should be given, therefore, to including measurements of the following, as appropriate:

(a) Gamma dose rate and integrated gamma dose and, if necessary, integrated neutron dose;
(b) Radionuclide concentrations in air and precipitation;
(c) Radionuclide deposition;
(d) Radionuclide concentrations in soil and surface and groundwater;
(e) Radionuclide concentrations in local foodstuffs (vegetables, fruit, grain, meat, mushrooms, drinking water, etc.);
(f) Radionuclide concentrations in terrestrial indicators (grass, lichen, mosses, etc.).

This section deals with monitoring of the air and radionuclide deposition. The next section deals with monitoring of the terrestrial environment.

4.3.1. Air monitoring

Airborne radionuclides may originate directly from discharge to the atmosphere and from resuspension of radionuclides deposited on soil or sediments.

Air sampling is undertaken to measure the aerosol-bound, vapour and gaseous radionuclide concentration in air. Air samples should be collected continuously at one or two permanent sampling stations in the vicinity of those facilities that discharge significant amounts of radionuclides to the atmosphere, particularly nuclear facilities. A reference sampler might be located in an area where the natural background and fallout levels are similar to those at the site, but where the influence of discharges from the facility is negligible. In addition, mobile air collection systems can be used temporarily at various sampling locations, as appropriate.

Consideration should be given to the following in relation to air sampling as part of a monitoring programme:

(a) Height at which the sample is taken;
(b) Collector location, taking account of the prevailing meteorological conditions and the dispersion characteristics of the discharge plume and where the highest radionuclide concentrations are to be expected;
(c) Siting of the collector with respect to abnormal meteorological or other environmental phenomena and large buildings;
(d) Sampling rate and total flow volume during the sampling period;
(e) Protection of the collector from damage and weather conditions;
(f) Potential impact of factors such as dust load on the collector.

Typical examples of air samplers employed in environmental monitoring are depicted in Fig. 4.

The frequency of radionuclide analysis should take into account the physical half-lives of the radionuclides of interest and the activity of the radionuclides being discharged. Analysis may be performed on every sample collected or, if frequent information is not required or the discharges of radionuclides are routinely low, samples may be combined to represent longer collection periods up to three months.

The filters should be analysed by the most appropriate methodology. Gamma spectrometry (HPGe) is a useful method for providing information on a wide range of radionuclides. For facilities with the potential to release strontium-90, composite samples should be analysed for this radionuclide. In the

FIG. 4. Large volume air samplers for the monitoring of aerosol-bound radionuclides. (Source: NRPA.)

vicinity of nuclear facilities with the potential for releasing alpha emitting radionuclides, the filters should be analysed for total alpha activity. If the alpha activity exceeds a predefined level, the filters should be analysed for specific radionuclides. Appropriate further information on the general monitoring of radioactivity in air can be found in Refs [95–99].

4.3.2. Deposition

The term deposition includes both wet and dry deposition. Dry deposition results mainly from the downward vertical fall of aerosols in the atmosphere but it may also result from other phenomena (e.g. sorption by soil and plant surfaces or impaction). Wet deposition results from the washout of radionuclides by precipitation. For discharges from stacks, the amount of deposited materials depends on the effective stack height (which takes account of efflux velocity and any buoyancy due to temperature differences) and the prevailing weather conditions. It is generally considered that dry deposition still occurs when it is raining or snowing, although in this case, the effect of wet deposition is much greater.

The deposition rates of radionuclides are much higher when it is raining or snowing than are the dry deposition rates. Monitoring programmes for deposited activity are usually carried out to measure the accumulation of radionuclides on the ground and to follow the dispersion of discharged radionuclides in the environment. Collectors are available for sampling wet and dry deposition separately, and these are discussed further in the following sections. However, for the purpose of routine monitoring, continuous sampling and subsequent measurement of combined wet and dry deposition are usually sufficient for all facilities, and separate measurement of dry deposition is necessary only in special

cases. An example of a special case is the growing of vegetables. As the extent of contamination of vegetables is different for the two types of deposition, the data obtained with collectors that sample the total deposition cannot be used to accurately assess food chain contamination. Thus, if only collectors for sampling the total deposition are used, the atmospheric aerosol concentrations should also be monitored as these can be used to calculate the dry deposition rate.

Where monitoring of dry deposition is required, collectors should be placed far enough from the stack to ensure that the plume has reached the ground. One collector should be placed downwind of the point where the dry deposition has been assessed to be at a maximum according to the local annual average weather conditions. Collectors should also be placed in the neighbourhood of the representative person. The installation requirements are essentially the same as for the collectors for sampling the total deposition.

Wet deposition is monitored by collecting rainwater or snow continuously in a device of known horizontal surface area [100]. The number of deposition collectors should be decided according to site specific factors. The sample vessels should be changed at least once a month, but the analyses can be made from composite samples representing longer periods. The frequency, however, may be adapted according to the weather conditions (i.e. a higher frequency during the wet seasons and a lower frequency during the dry seasons). The samples should be analysed for the radionuclides potentially released by the nuclear facility.

Collectors should be installed according to the following considerations:

(a) Position relative to overhanging trees, buildings or other objects that may affect the deposition process (see Fig. 5);
(b) Potential disturbance which may cause resuspension (i.e. it is not advised to install in industrial or agricultural areas);
(c) Potential bias in the sampling due to angled positioning.

When used in cold climates, they should be able to collect snow.

At least one collector should be placed at a site of expected maximum concentration (this will be based on the most probable wind direction with precipitation) and at least one should be installed at the site where the population is expected to receive the highest dose. A reference collector should be located at a site that is essentially unaffected by the discharges from the facility. For emergency situations, it is advantageous if the deposition collectors and the air samplers are installed in parallel, so that the results complement each other in the determination of the radionuclide composition.

FIG. 5. Appropriately sited collection devices for the monitoring of wet deposition of radionuclides. (Source: IRSN.)

4.4. TERRESTRIAL ENVIRONMENT

Radionuclides may be introduced to the terrestrial environment as a result of deposition from the atmosphere or due to irrigation. Thus, in establishing environmental monitoring programmes of the terrestrial environment, consideration should be given to measurements of the gamma dose rate and integrated gamma radiation level and radionuclide concentrations in soil, foodstuffs (vegetables, fruit, grain, meat, mushrooms, drinking water, etc.) and indicator materials (grass, lichen, mosses, etc.). Such programmes should complement the monitoring of the concentration of radionuclides in air, radionuclide deposition and irrigation water. The following section focuses primarily on monitoring around nuclear facilities.

4.4.1. External radiation

External radiation is caused by the accumulated deposition on the ground of radionuclides discharged to the atmosphere from a facility, exposure to radionuclides in air as well as any direct radiation from the facility itself, which is dealt with in Section 3.6. For facilities releasing beta/gamma emitting

radionuclides to the atmosphere, the external dose rate should be monitored not just at the boundary fence but also in the surrounding area.

To monitor the external dose rate due to routine discharges, integrating dosimeters are used. The number and distribution of dosimeters should be determined according to site specific factors including the significance of the atmospheric discharge, but the stations chosen should include those points where external dose rate is expected to be at its highest, as well as the locations of any representative person. The network of monitoring stations should also include a reference station at a location that is essentially unaffected by the discharges from the facility. The recommended height for the dosimeter is 1 m above the ground. Dosimeters should be placed in locations that are free of buildings, trees or other objects that might shield them from the radiation. The dosimeters should be changed every 3–6 months.

For nuclear power plants and reprocessing plants, consideration should be given to installing a system for recording the dose rate continuously at one or more stations in the vicinity of the facility [70–74, 79, 101]. The location of the dose rate meters should be decided according to site specific factors but they are generally located in the direction where the highest external dose rates are expected. A sufficient number of continuously recording dose rate meters may also be a very valuable support in the event of an accident (see Section 5).

4.4.2. Soil

Monitoring of the radionuclide concentrations in soil is carried out to provide information on the buildup over time of deposited radionuclides in the terrestrial environment. Such information can be used with transfer coefficients to estimate the uptake of radionuclides from soil by plants. The contribution of a facility to the soil activity is often difficult to estimate, because of the presence of radionuclides, particularly caesium-137 and strontium-90, from the fallout from the atmospheric testing of nuclear weapons, and of uranium and other radionuclides of natural origin. Any increase in the concentrations of these radionuclides can only be determined by reference to the pre-operational measurements of them. Normally, monitoring involves the sampling of soil (Fig. 6) for subsequent measurement in the laboratory. However, in situ HPGe gamma spectrometry may also be used to detect changes in soil concentrations.

Soil samples should always be taken from the same sampling points in order to ensure that comparable data are obtained. They should be taken from an undisturbed (unploughed) area of ground, which is free of large stones or roots and relatively open without sheltering trees, in order to evaluate the long term impact of deposited radionuclides. Depth profiles are recommended for a full soil

FIG. 6. Soil sampling for the monitoring of deposited radionuclides, employing a soil corer. (Source: IRSN.)

characterization. However, routine analysis of the depth profile may not be necessary to detect long term accumulation.

Soil samples may also be taken of agricultural soil as part of a programme to study the ingestion pathway. In these circumstances, it would also be appropriate to take the agricultural samples, such as vegetables, from the same place.

Soil sampling should be conducted in such a manner and in such a way that cross-contamination, either between samples or between sampler and sample, does not occur. Typical materials include plastic and stainless steel devices. Precautions should be taken, when using corers or similar devices, that surface material is not carried down the core to contaminate lower layers. Similarly, extensive distortion of the core via compression or elongation should be avoided during sampling.

The sampling of soils can introduce a variety of uncertainties and errors into the final quantitative result and precautions must be taken to ensure the quality of

data generated from such samples. Appropriate information should be recorded during sampling regarding any aspect that may affect the final analytical result. A large body of literature exists as to correct procedures for the taking, storing and preparation of soil samples. References [102–106] are useful guides. Although a wide range of methods have been reported for the analysis of soil samples for radionuclides, adoption of methods for such analysis should be based on authoritative sources. Appropriate sources include Refs [107–113]. Useful recommendations as to soil sampling terminology can be found in Ref. [114].

4.4.3. Foodstuffs

The objective of routine monitoring of foodstuffs around a facility is mainly to verify the results of the source monitoring programme and to determine the doses to members of the public. Plants, animal products and drinking water in the vicinity of a facility discharging radionuclides to the atmosphere should be included in the environmental monitoring programme. The samples should be collected from areas expected to receive the highest levels of contamination, be typical of the areas and related to determining the exposure of any representative person. Reference samples should be obtained from locations unaffected by the facility. Reference data may also be available from a nationwide monitoring programme. The layout for a standard method of sampling from a lot of agricultural food products is provided in Ref. [115].

4.4.3.1. Plants

Plants are primarily contaminated, during routine and emergency releases, by direct deposition of aerosol-bound and gaseous radionuclides or by direct contamination via resuspended (by wind or rain splash) radionuclides. Root uptake is usually of minor importance, although not always. For example, root uptake may be a more significant route of plant contamination with long lived radionuclides. It may also dominate once the release has ceased. Nevertheless, leafy vegetables are normally good indicators for determining the influence of a facility on the contamination of plants.

Sampling of plants (Fig. 7) that are typical of the diet of the representative person is preferred. It should concentrate on the edible part of the plant and should be performed near the harvesting period. The exact location where the plant has grown (sampling in the field) should be reported when possible, not where the product has been purchased (sampling from markets). Greenhouse production should be avoided. Usual locations for sampling are in the direction of prevailing winds, close to the location of maximum expected deposition. Samples

FIG. 7. Sampling of agricultural vegetables. (Source: IRSN.)

should be collected on open areas (undisturbed deposition) as far as possible. Typical local species should be preferred. Care should be taken to ensure that adhering soil particles are not included 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 subsequent transfer to milk. Pasture should be sampled at the locations where the wet and/or dry deposition is expected to be at its highest. Samples of milk and undisturbed soil should also be collected at the same locations.

The area to be sampled should be selected carefully. It should be nearly horizontal and flat in an open area, free from large trees or buildings. Plants should be uniform in growth height. Typically, areas of 1 m^2 or more are sampled, in order to obtain about 1 kg of samples: grass is collected down to a few centimetres above the ground; only the green leafy portion of the plants is collected. Care should be taken not to include soil. Sampling tools should have been cleaned with water and dried with fresh paper tissue, and samples sealed in plastic bags.

All plant samples should be analysed for the radionuclides discharged from the facility. For example, the monitoring programme around a nuclear power plant may include analysis using HPGe gamma spectrometry and include the measurement of iodine-131. Strontium-90 should also be measured in selected samples. In addition, tritium, carbon-14 and alpha emitters should also be analysed in a selection of samples.

Appropriate information about the analysis of plants for radioactivity can be found in Refs [116, 117].

4.4.3.2. Animal products

Milk (from cow, goat or sheep) is often the most important animal product to be monitored for several reasons: large quantities may be consumed by the population; radionuclides deposited on grass are consumed by animals grazing on pasture and certain radionuclides are transferred effectively to milk; the milk can be consumed soon after milking, with the consequence that there is little opportunity for radioactive decay of any short lived radionuclides. Furthermore, milk is a very good indicator of the contamination of animal products in general by iodine-131 and caesium-137. Due to its short half-life, iodine-131 in milk should be analysed frequently, depending on local agricultural practices (e.g. monthly). Detailed guidance on the sampling of milk and milk products is given in Ref. [118].

In the vicinity of reprocessing plants and repositories, additional analyses of iodine-129 and carbon-14 in milk might also need to be undertaken.

Where milk is to be sampled, it should be taken from local dairy farms where the cattle graze on pasture close to and downwind of the facility and in the most contaminated area. Milk should be collected in clean containers and refrigerated if measurement is to be made the following day. If the sample is to be stored, a preservative will need to be added. Usually, a sample of a few litres is sufficient. Information as to the measurement of radionuclides in foodstuffs can be found in Refs [117, 119, 120].

As the uptake of radionuclides into meat is relatively slow in comparison to that into milk, less frequent sampling of meat is required. Samples may be composites of subsamples.

As the alpha emitting radionuclides (isotopes of uranium, plutonium, americium, etc.) are not readily absorbed in the gut of animals, the contamination of milk and meat by these radionuclides is low and animal products do not usually need to be monitored.

Other animal food products should be monitored as appropriate.

4.4.3.3. Drinking water (for humans and animals)

Where groundwater is a major source of drinking water, as no rapid changes in the radionuclide concentration would be expected during routine discharges and in areas contaminated by long lived radionuclides, analysis of annual samples would normally be sufficient.

Where drinking water is taken from a lake, pond or river located close to a facility, more frequent sampling may be required, especially in emergency situations. The samples should be analysed for the relevant radionuclides. Samples of drinking water taken for the purpose of monitoring levels of radioactivity should be treated in a manner such that the sample is representative. Careful consideration should be given to filtration and sample preservation techniques applied to the sample and how they may affect the extent to which the sample is truly representative in relation to what is actually consumed.

Special consideration should be given to the monitoring of water around uranium mines and waste management facilities. Thus, in the case of in situ leaching (ISL) uranium mining, a sufficient number of groundwater samples should be taken to verify the predicted operation of the extraction well field and compliance with any contamination limits prescribed by the regulatory body. In the case of open pit and underground uranium mining, monitoring of seepage water from the intermediate containment ponds should be undertaken. Monitoring of groundwater should also be necessary around, above and below ground waste management facilities. The level of monitoring required will depend on whether the groundwater interacts with any groundwater used for drinking purposes. Detailed information as to the sampling and analysis of environmental waters for radioactivity can be found in Refs [116, 117, 121–129].

4.4.4. Indicator materials

Indicator materials can provide information during the routine operation of facilities on short term and long term changes of radionuclide concentrations in the environment, which would not necessarily be detected in foodstuffs. Possible indicator materials are lichen, moss, leaves, pine needles, etc. However, these materials are not appropriate for the purpose of determining the dose to members of the public from discharges of radionuclides from a facility. Their usefulness lies in the fact that they provide information on trends and environmental accumulation.

Only indicators that are easy to collect and measure all year long should normally be included in a monitoring programme. If indicators are included in

FIG. 8. Sampling of terrestrial indicators as part of an environmental monitoring programme: (left) lichen; (right) mosses. (Source: NRPA/IRSN.)

environmental monitoring programmes to identify long term trends, care should be taken to ensure that the same species is collected at the same stage of growth each year (Fig. 8). Indicator materials may be selected on the basis of their uptake of various radionuclides. In this manner, better sensitivity may be obtained by selecting organisms which take up higher levels of various radionuclides than others. Typical examples in this context include various species of seaweeds that take up technetium-99, shellfish species that take up plutonium and strontium isotopes, and various terrestrial plant species that are known to accumulate caesium isotopes efficiently.

4.5. AQUATIC ENVIRONMENT

Radionuclides discharged to the aquatic environment (sea, lake or river) can lead to exposure of members of the public from:

(a) Ingestion of radionuclides that have been incorporated into foodstuffs taken from the aquatic environment;
(b) Plant and animal food products produced on irrigated land;
(c) External radiation from radionuclides in contaminated sediments, water, etc.

For the monitoring of potable water abstracted from freshwater supplies, see Section 4.4.3.3.

In establishing environmental monitoring programmes for liquid discharges, consideration should be given, therefore, to including measurements of the following:

(a) Radionuclide concentrations in water;
(b) Radionuclide concentrations in foodstuffs (fish, shellfish, etc., and agricultural crops, where the water into which the discharge takes place is used for irrigation purposes);
(c) Radionuclide concentrations in indicator materials such as seaweed, marine sponges and benthic animals;
(d) Radionuclide concentrations in air due to sea spray and resuspended sediments, etc.;
(e) Gamma dose rate and integrated gamma dose from contaminated sediments and water.

Routine environmental monitoring programmes should provide information on the long term trends of activity concentrations or dose rates in the aquatic environment, verify the results of the source monitoring programme and provide information that is necessary to assess the doses to the representative person.

The monitoring programme should take account of:

(a) Local circumstances and characteristics of the receiving water body (e.g. prevailing water currents, complicated archipelago area/open sea coast, and local topography and depth relations);
(b) Main migration directions of discharges in the environment, and the affected centres of population;
(c) Expected activity concentrations of discharged radionuclides in the aquatic environment;
(d) Local weather conditions (e.g. whether the recipient water body is covered by ice for several months of the year);
(e) Use of the aquatic environment for recreational and commercial purposes.

As with the monitoring of the terrestrial environment, the sampling points should be chosen with reference to the doses to the representative person. In addition, it is recommended that a reference station be established in a location unaffected by discharges from the facility so that appropriate comparison of the results of monitoring can be made and the incremental contribution from the facility can be assessed. In the case of discharges to a river, a reference station upstream of the discharge point would be appropriate.

The inhalation pathway is not usually important in the case of discharges to the aquatic environment. However, this pathway may contribute to the doses to humans when significant levels of radionuclides (particularly alpha emitters) are present in exposed sediments or in suspended solids in sea water.

FIG. 9. Sampling of water for radioactivity monitoring: (left) marine sampling from a boat; (right) marine sampling from the shore. (Source: NRPA.)

4.5.1. Environmental waters

A good water sampling strategy provides information on the migration and the activity concentrations of radionuclides in the water body into which the discharges are made (Fig. 9). These details can be used for the verification of models of the movement of radionuclides in the water body and for the calculation of the concentrations of these radionuclides in other aquatic media, and for the derivation of transfer coefficients between water and these other media.

Owing to the fact that liquid discharges are often made in batches, the concentrations of radionuclides in water samples at any one point in time may vary considerably. Continuous water sampling will give the time average concentrations, which is important if the water is used for consumption. Sampling may also be necessary during the discharge of radionuclides from an accumulation tank. Sampling during discharge operations, either continuously or at a time representative of the discharge operation (e.g. mid-time), is used to control the effective dispersion of the discharge (including the correct discharge flow) and to detect any abnormal situation.

Where the water is used for irrigation, specific sampling should be performed during the relevant period, at a location close to the point from which it is extracted.

Samples of a few litres are usually enough for routine measurements. Containers should be rinsed with some of the water to be sampled. When sampling, care should be taken to avoid the collection of sediment and other

extraneous material. Samples generally should be filtered and stabilized (acidified) to avoid deposition of the radionuclides on the container walls. The samples should be analysed by gamma spectrometry and for tritium. Strontium-90 might be analysed in selected samples. Alpha emitting radionuclides and other beta emitters may need to be analysed in the vicinity of nuclear facilities releasing these radionuclides. Relevant information on sampling and analysis can be found in Section 4.4.3.3 (Refs [116, 117, 121–129]) and in Refs [130–134].

4.5.2. Sediments and suspended particulate material

Many radionuclides discharged into water are significantly adsorbed onto particulate material which accumulates with time as bottom sediment. Bottom sediments can be used, therefore, as indicators of contamination due to past discharges, the upper layers of sediment being the more recent. Moreover, marine coastal sediments in the tidal zone or freshwater bank sediments may result in external exposure of people who spend time on them for occupational (farming, fishing) or recreational (boating, fishing) purposes. Sediments may also be deposited on low lying grazing land during periods of flooding or unusually high tides. Sediment is also part of aquatic food chain contamination, as many organisms live in or on the sediment or use sediment as a food source. Therefore, the monitoring of sediments (Fig. 10) should be carried out as part of a programme to determine the external radiation exposure of members of the public and the overall impact of the discharges on the aquatic environment. Analysis of sediments may also reveal the presence of contamination not detected by the monitoring of water or other samples.

There are three main types of sediment monitoring:

(1) Surface sediment monitoring. This monitoring is performed in order to obtain data on contamination due to recent discharges. Such monitoring should be performed with a rather high frequency, from monthly to annual. The main difficulty is obtaining undisturbed samples from the surface layer, because of the soft and mobile nature of the surface layers.
(2) Suspended sediment monitoring. This monitoring has the same objective as surface sediment monitoring. Sediment particles are collected by sediment traps placed above the bottom (typically, 1 m above the sediment surface). The typical sampling frequency is from monthly to quarterly.

FIG. 10. (a) Sampling of surface sediments; (b, c) lower layer sediment sampling; and (d) sectioning of sediment monolith. (Sources: IRSN/NRPA.)

(3) Lower layer sediment monitoring (sediment core monitoring). This monitoring is performed to obtain data on the contamination due to past discharges. Such monitoring can be performed with a low or very low frequency, from yearly to by decade. The main difficulty is to obtain undisturbed samples from the lower layers. Samples are sectioned into slices and the radionuclide contamination of each slice is measured independently to obtain data on the vertical distribution, that is, on the history of the contamination pattern. The thickness of the slices should be consistent with the particle deposition rate, so that one slice represents a defined period of time.

The accumulation of radionuclides in sediments is highly dependent on the particle size distribution of the sediments. This implies that:

(a) Monitoring programmes may need to specify the particle size distribution of the samples to be taken.
(b) Sediment should always be collected in the same place to increase the probability of obtaining the same particle size distribution and in order to observe both short term variations and long term trends.
(c) Comparison between the contamination of sediments collected upstream and downstream should take into account the possibility of bias due to differences in particle size distribution.
(d) Particle size distribution should be monitored, at least periodically for the surface sediment samples, and for the various slices from sediment cores.
(e) Data obtained from fine particle sediments may not necessarily provide a good basis for calculating doses from external radiation to people who spend time on coarse particle sediments (e.g. beach sand). In this case, additional sampling should be conducted.

Sediment sampling should be conducted downstream of the facility outlet. For facilities that discharge into rivers, sediment sampling should be performed at places where the discharges are reasonably well mixed with the river water. The locations used should never dry out, even during periods of drought. For facilities that discharge into lake water or sea water, the locations should be based on a study of the dispersion of the radionuclides.

Gamma dose rates should be measured (at a height of 1 m) over exposed sediments and inundated grazing land. The number or measurement points chosen will depend on the areas affected. The chosen measuring areas should be representative of those areas used by people in the course of their professional activities (e.g. farming) or of leisure pursuits (e.g. boating, fishing). Analysis of sediments is typically undertaken as for soils. Useful guides to ensuring quality in sediment sampling are to be found in Refs [135–137].

4.5.3. Aquatic organisms

Aquatic biota of interest include fish (both pelagic and benthic), shellfish (mollusc and crustacean) and plants (mainly seaweed in sea water). Aquatic biota may be foodstuffs (specific species of fish and shellfish, seaweed in some countries), bio-indicators for certain radionuclides (molluscs, seaweed) and/or part of the terrestrial food chains (seaweed used as fertilizers). Some species are highly mobile (many species of fish and crustaceans), others are not (molluscs and seaweed).

Aquatic foodstuff consumption is often a significant if not the predominant exposure pathway for liquid discharges from nuclear facilities. Comprehensive aquatic biota monitoring programmes are therefore often necessary. If aquatic foodstuffs represent a significant pathway of exposure, a survey of the quantities of locally caught species and their seasonal variations should be carried out. Some consideration of the consumption of seaweed may also be required.

The monitoring programme should concentrate on those species of aquatic foodstuffs — local fish, shellfish and edible seaweed — that are consumed by the representative person. Measurements should concentrate on the edible part of samples. The specimens taken should reflect the mix of size and age representative of those actually eaten. For small fish, this may include bones, but most of the time only flesh or even only some muscles of animals are effectively consumed and, therefore, should be measured separately. In addition, seaweed that is used as a fertilizer should be included in the programme.

The mobility of many aquatic organisms and the large diversity of the biota in the marine environment make the selection of control species difficult. The habits (benthic, predatory or prey), mobility and migration of the species should be taken into account. The number of control species should be decided according to site specific factors.

4.5.4. Indicator samples

Indicator materials may not necessarily give rise to exposure of members of the public, but they may be used to monitor short term and long term trends in radionuclide concentrations in the aquatic environment. Indicators that might be used include plants, algae, benthic animals and inorganic materials (e.g. suspended particulate matter), which effectively accumulate radionuclides from their medium.

The indicator species should, therefore, be easy to collect, should be abundant in the area of interest, relatively large in size and resistant to environmental changes. In the marine environment, seaweeds, molluscs or crustaceans are frequently used as indicators of discharges of radionuclides, for example, cobalt-60, cobalt-58, manganese-54, technetium-99, caesium-137, and some transuranic elements. Fish bones and seashells may also be used as indicators for strontium-90.

4.6. MONITORING REQUIRED FOR THE DETERMINATION OF ATMOSPHERIC AND AQUATIC DISPERSION

The meteorological and hydrological parameters of the environment determine the dispersion of the radionuclides following discharge and, therefore, should be measured. These parameters are also relevant for accidental releases.

The following parameters should be monitored for use in an appropriate dispersion model for the purposes of assessing doses from discharges to the atmosphere [14, 138]:

(a) Wind direction;
(b) Wind speed;
(c) Precipitation;
(d) Parameters for the determination of the effective height of release (ambient temperature, temperature and volume flow in the vent air stack);
(e) Any other parameter that is of importance for determining the dispersion and atmospheric transport of radioactive materials, such as the vertical temperature gradient in the atmosphere.

Further details on the monitoring of atmospheric conditions are given elsewhere [139].

The following parameters should be monitored for use in an appropriate aquatic dispersion model for the purposes of assessing doses from discharges to the aquatic environment [140]:

(a) Water course flow rates;
(b) Prevailing water currents in the discharge area;
(c) Changes in water level;
(d) Ice conditions (if relevant);
(e) Any other site specific hydrological factor that influences the aquatic dispersion or accumulation of discharged radionuclides in the environment.

4.7. PECULIARITIES OF ENVIRONMENTAL MONITORING OF MULTIPLE SOURCES

Environmental monitoring related to multiple sources might be required when authorized discharges from more than one facility affect the same environment. Nevertheless, a situation may exist where two or more facilities make non-negligible contributions to the exposure of the representative person. Such sources should be treated as an aggregated source and an appropriate

representative person defined. If there is more than one facility in the vicinity discharging radioactive material to the environment, this will need to be taken into account in the environmental monitoring programme discussed earlier for a particular facility.

The contamination of the environment due to airborne discharges of radionuclides decreases rapidly with the distance from the plant. Usually the single source related monitoring programmes established by each authorized person are sufficient. Additional measurements would only be necessary if non-negligible cumulative and additive effects of the discharges might be anticipated.

If more than one facility discharges radionuclides into the same river or lake, it might be necessary to quantify the contribution of each of them to the exposure of an appropriately defined representative person. For discharges into the same river, the registrant or licensee of any downstream facility should monitor the aquatic environment upstream of the location of his/her discharge. The measurement should cover the activity of the relevant radionuclides in water, sediment and fish. For comparison purposes, the upstream and downstream samples should be taken at the same time. Sampling and measurement should be carried out in accordance with the above recommendations on environmental monitoring in general. For discharges into the same lake, separation of the contributions from each facility may be more difficult and would involve detailed studies of the distribution patterns of the radionuclides in the aquatic environment.

The additional measurements should reflect the relevance of the exposure pathway and focus on the radiologically more significant radionuclides. The monitoring should be undertaken in accordance with the recommendations on environmental monitoring in general.

5. SPECIFICITY OF MONITORING DURING AND AFTER AN ACCIDENTAL RELEASE

5.1. EMERGENCY MONITORING OF THE SOURCE

Although decisions regarding the countermeasures to be taken in the event of an accidental release of radionuclides depend on plant conditions and environmental measurements, information on the activity of the radionuclides released (the source term) is of vital importance [5, 19–22]. This is particularly so in

the case of accidental releases to the atmosphere. The source monitoring systems should at least be able to provide data on the most significant radionuclides released. For reactor accidents, both short lived and long lived radionuclides need to be considered. These include the isotopes of noble gases (e.g. isotopes of krypton and xenon) and of tellurium and iodine (in particular, iodine-131), and volatile radionuclides, particularly isotopes of caesium (caesium-134 and caesium-137). For other nuclear fuel cycle plants, the release of the long lived radionuclides (such as the isotopes of caesium, strontium-90) and alpha emitters (such as the isotopes of uranium, plutonium and americium) need to be considered.

The monitoring systems for discharges from nuclear facilities should also be adequate for measuring the much higher activity concentrations that might be released under severe accident conditions. It is usually not considered sufficient to be able to monitor only the range of activity concentrations that might result from a design basis accident. For power reactors, the upper bounds of the dynamic range for monitors measuring releases to the atmosphere is typically of the order of 10^{15} Bq/m^3 for noble gases, and 10^{14} Bq/m^3 for iodine-131 and particulate activity. However, these bounds may be reduced if the containment is such that a substantial reduction of the possible activity released under accident conditions can be assumed.

For the purpose of monitoring noble gases in the event of an accident, a practical approach is to use a gamma detector and to calibrate it for krypton-88 and xenon-133. On-line iodine monitors should be such that they are sufficient to be able to distinguish between iodine-131 and the other iodine isotopes (iodine-132, iodine-133, iodine-134 and iodine-135). This requires high resolution gamma spectrometry.

If a continuous filtering system is deployed for monitoring isotopes of iodine and particulate material, a wide measuring range can be obtained by increasing the distance between the filter and the detector or by only measuring parts of the filter. Where this is done, provision should be made for handling the highly radioactive filters to protect personnel and prevent the spread of contamination. The detectors should be calibrated for measuring high activities on the filters at various distances.

If possible points of release of radionuclides other than the monitored stack have been identified in the safety analysis for the facility, an assessment should be made of the feasibility of obtaining appropriate monitoring data. Possible options would be to monitor the activity concentration in the containment air or appropriate ducts, or the dose rate at specific locations within the containment.

For both atmospheric and liquid accidental or abnormal releases, the monitoring programme should be altered to ensure that the sampling will adequately characterize the impact with respect to both time and space. The robustness, reliability and upper bounds of the dynamic range of measurement

systems for both atmospheric and liquid releases should be appropriate for the conditions prevailing during and after the release.

Useful information on monitoring systems for accident and post-accident situations in nuclear power plants can be found in Refs [141–145].

5.2. MEASUREMENTS DURING THE PASSAGE OF A CLOUD

In the event of an anticipated operational occurrence which may result in accidental releases or an acute accidental release, the existing emergency monitoring network should be activated and appropriate mobile measurement systems deployed immediately to assess the radiological situation in the affected area, or the potentially affected area, for the purpose of decision making regarding the countermeasures to be taken to protect members of the public. The important exposure pathways during the passage of a cloud are radiation for beta and gamma emitting radionuclides in the cloud and inhalation of radionuclides. Emergency response is dealt with in other IAEA publications [5, 19–22] and therefore is not discussed in detail here. The IAEA Safety Standards require authorized persons as well as the relevant local and national emergency response bodies to have established appropriate plans in place [5]. This report focuses only on the monitoring that should be undertaken by the licensee and designated agencies, which should have in place arrangements for the off-site monitoring of the following during the passage of a cloud:

(a) External dose rate;
(b) Radionuclide composition in air.

5.2.1. External dose rate

Routine monitoring of the external radiation environment around a facility is discussed in Section 4.4.1. In particular, reference is made to the establishment of a network of stations for monitoring — using on-line electronic dose rate meters (Fig. 11) and off-line integrating dosimeters — the external radiation field around sites that discharge radionuclides to atmosphere. In establishing such a network of monitoring stations, account should be taken of the need to monitor the external radiation field in the event of a serious accidental release of radionuclides to the atmosphere.

The information from any systems for recording the dose rate continuously should contribute to the understanding of the radiological situation off-site. Such systems should automatically transfer the information on-line to the licensee and

FIG. 11. Continuously monitoring dose rate meter for emergency monitoring. The device mounted horizontally is a rain meter to allow for compensation for the washout of natural radionuclides by rain. (Source: NRPA.)

designated agencies. The frequency of measurements during passage of the cloud should be at least every 10 min during this phase. This will provide information on the movement of the cloud and the affected areas.

About 12 fixed monitoring stations situated in a ring around, and at a distance of about 2–3 km from, a nuclear power plant is recommended. Consideration should also be given to locating them in nearby villages and towns. The availability of electric power and telecommunication lines, their accessibility for maintenance, and the need for physical protection are also important factors that will need to be taken into account in determining the actual location of the monitoring stations.

Additional measurements of the external dose rates off-site should be started as soon as there is an indication in the plant that a significant release of

radioactive material may occur. These should be undertaken using mobile systems with direct transfer of the data to the on-site emergency centre. The choice of the measuring sites for the mobile systems depends primarily on the wind direction. Due account should be taken of the need to protect the technicians involved in undertaking the monitoring.

As with the monitoring of external radiation fields resulting from routine discharges, measurements should be made following a predefined standard procedure. In particular, measurements should be made at a height of 1 m above ground.

The dynamic range of monitoring systems should be capable of covering all dose rates that might be encountered. Because of the wide range of possible external radiation dose rates, a combination of two energy compensated Geiger–Müller tubes is recommended, one covering the low dose rate range from 20 nSv/h to 2 mSv/h, the other covering the high dose rate range from 0.1 mSv/h to 10 Sv/h.

The results of gamma monitoring should be presented on a map to facilitate decision making.

5.2.2. Radionuclide activity in the air

Up to 100% of the radioactive noble gases are released from a degraded core in the event of a serious reactor accident. The main exposure pathway is via external irradiation and their contribution to the inhalation dose is comparatively low. Consequently, it may not be a priority to analyse the noble gas composition in air. It is, however, necessary to measure all other radionuclides, depending on the nature of the source term.

For the purpose of monitoring these materials off-site, the air collecting and measuring systems used for monitoring the impact of routine discharges should also be able to provide information in the event of an accident. When using fixed-filter systems, the filters have to be measured directly after sampling, using HPGe gamma spectrometry. As it is time consuming to undertake alpha spectrometry, a measurement of the gross alpha activity on the filter should also be made in the first instance, without any chemical treatment or separation. Radionuclide specific analyses for alpha emitters should be anticipated at a later stage when there is more time available. The use of energy selective on-line alpha detectors may be considered for particular circumstances.

Automatic step band filter systems can be used for on-line monitoring. These include an HPGe detector for gamma ray spectrometry and detectors for the measurement of alpha and beta activities. They often also include a charcoal filter, placed after the filter that extracts the aerosols, to sample the isotopes of

iodine in elemental or organically bound form. The isotopes of iodine can be measured using a NaI detector.

5.3. MONITORING AFTER PASSAGE OF THE CLOUD

After passage of the cloud, monitoring of the following should, as appropriate, be undertaken:

(a) External dose rate;
(b) Deposition of radionuclides on soil;
(c) Contamination of fresh food and feed stuffs;
(d) Contamination of the aquatic environment.

Such monitoring is necessary in order to determine whether any countermeasures applied during the passage of the cloud can be lifted, and whether any further countermeasures should be introduced, such as relocation of people in the affected area, restriction of access to contaminated areas, restrictions on the consumption of foodstuffs, and decontamination of the urban environment. The imposition of such countermeasures should be based on pre-established intervention levels. In the event of a severe accident resulting in widespread contamination of the environment, responsibility for the management of the response, including the coordination of the environmental monitoring programme on which the response is based, lies with the relevant national authorities. This section provides an overview of the measurements that should be undertaken. Further information is given in the relevant IAEA Safety Standards and supporting publications [5, 20–22].

5.3.1. External dose rate

Once the cloud has passed, a comprehensive survey of the gamma radiation levels in the affected areas should be undertaken (Fig. 12) in order to develop a comprehensive overview of the deposition of radionuclides and where further investigation may be necessary. The information should be supplemented by information from national monitoring networks that have been installed in some countries in order to cover a much wider field than that established by the operator of a nuclear facility.

Particular attention should be paid to whether there are areas of significantly enhanced deposition such as might have occurred through washout by rain. Mobile systems mounted in cars are useful for determining such areas

FIG. 12. In situ gamma measurement system for the monitoring of deposited activity after an accident situation. (Source: NRPA.)

around the affected plant. Larger areas can be surveyed by equipment mounted in helicopters [146].

The physical half-lives of many of the radionuclides released in a nuclear reactor accident are short and, consequently, the external radiation levels will decline rapidly over the days immediately following the passage of the cloud. Consequently, measurements — in particular, in the vicinity of the facility — could be repeated with a frequency of once a day until the levels stabilize.

In urban areas, measurements of the external dose rate give an overview of where further countermeasures, such as decontamination, might be needed. External dose rates should be measured with portable dosimeters covering a range from 50 nGy/h up to 1 mGy/h.

5.3.2. Soil deposition

In situ measurements are very useful for rapidly determining the composition and the amount of the deposited gamma emitting radionuclides [147, 148]. It is noted that the composition of the deposited radionuclides will vary with the distance from the source, due to their different physical properties

— volatility, particle size, etc. In situ measurements will provide information on this variation.

The equipment for in situ measurements using gamma ray spectrometry should be capable of being transported in the survey vehicles. The measurements should be made with a HPGe gamma detector with a relative efficiency of 10–20%. Higher efficiencies may lead to counting difficulties when the contamination levels are relatively high due to the 'dead time'. Additionally, a multichannel analyser (MCA) with high voltage supply, amplifier and ADC unit (or digital data processing) and a laptop for data evaluation are needed. The use of systems which use radio communication between the MCA and the laptop avoids the need for cables which might otherwise become contaminated. The detector should preferably be installed at 1 m height so that the measurements are directly comparable with those of the gamma dose rate. The absolute values of the deposited activity are obtained by subtracting the background spectra, which should have been measured in advance, from the actual measured values. Suitable practical precautions should be taken in making these types of measurements, to avoid contamination of detectors and associated equipment as well as the survey vehicle and personnel involved.

Measurement of the deposition of gamma emitting radionuclides can also be made by sampling and subsequent analysis in the laboratory using an HPGe detector. The samples should be well mixed and measured in a Marinelli beaker.

The deposition of alpha or beta emitting radionuclides should be estimated by soil sampling followed by laboratory analysis. Radiochemical analysis in the laboratory, however, takes time and requires some experience.

The results of in situ gamma monitoring and sampling for the measurement of alpha and beta emitting radionuclides should be used to develop a map of the deposition of radionuclides in the environment. The quality of the map will depend mainly on an adequate number of measurements having been made.

5.3.3. Food and feedstuffs

The contamination of plants by direct deposition resulting from an accidental release to the atmosphere of radioactive material is usually higher by several orders of magnitude than that by root uptake. Consequently, immediately after the passage of a cloud, monitoring of foodstuffs such as leafy vegetables should be undertaken to determine whether any reference levels established by the national authorities will be exceeded. This monitoring should be adequate regarding the use of the monitoring results (e.g. foodstuffs should not be washed before measurement if the intention is to compare the contamination level of the foodstuff with a reference level, but may be washed for the purposes of dose estimations).

Another approach to estimating contamination of foodstuffs would be to use deposition data as a basis for the estimation of the activity concentrations in foodstuffs using appropriate models.

Reference levels for the contamination of foodstuffs are given in the BSS [2]. The values were developed by the joint WHO/FAO Codex Alimentarius Commission following the Chernobyl accident [149]. The values were applicable to trade in foodstuffs during the year following the accident. The Codex values have since been revised [150] and now apply to international trade with no restriction on time. Separate values may need to be developed by the affected country according to the needs of the country. There are also European requirements relating to the contamination of foodstuffs [151].

In the event of a serious accident at a nuclear power plant leading to an airborne release of radionuclides, the critical radionuclide will be iodine-131 during the first few weeks. This is because it may be released in large amounts and the deposition velocity of the elemental form of iodine is high. Isotopes of caesium are also of interest both in the short and longer term because they form a major part of an accidental release to the atmosphere. Both elements following deposition onto grass are readily transferred to milk.

The monitoring of foodstuffs will depend on the season during which the release has taken place and the agricultural practice in the affected areas. However, as a general rule, the focus of monitoring programmes should, in the first instance, be on leafy vegetables and milk. These can also act as indicators of the possible contamination of other plants and animal products.

For decision making, random sampling followed by an HPGe gamma spectrometric measurement is recommended. Alpha and pure beta emitters should be analysed if the corresponding radionuclides are expected to be present.

5.3.4. Aquatic environment

Contamination of water could occur following a direct release of radionuclides into a water body. In addition, consideration should be given to the possible contamination of water, including drinking water, as a consequence of runoff from land onto which radionuclides have been deposited following an accidental release to the atmosphere. Only open surface water sources need to be investigated in this early phase.

5.3.5. Natural environment

The natural environment, especially forest sites, might have a significantly higher level of contamination than agricultural and urban areas. To investigate the deposited activity, the external dose rate measurements and radionuclide

determination in some natural food products should be carried out. For the majority of situations, however, in emergency conditions, assessment of forest contamination does not have the highest priority in the early phase of the accident. The basic measurements have to be carried out as soon as the radiological situations in agricultural and urban areas have been investigated.

5.4. LONG TERM MONITORING

The aim of the monitoring programme is to determine how the levels of radionuclides in different environmental media change with time. In particular, the monitoring of foodstuffs will need to continue until the levels are below the relevant reference levels established by the national authorities and restrictions can be lifted. The focus of monitoring will be on the long lived radionuclides, particularly the isotopes of caesium, but other radionuclides may need to be considered depending on the radionuclides released during the accident. Caesium very often is strongly bound within the soil. However, under some conditions, particularly where the soil is poor in minerals, the caesium can be taken up through the roots into plants. Caesium in plants can transfer to the meat of animals grazing on them.

Monitoring is also necessary in order to determine when other long term countermeasures, such as the relocation of sections of the population, can be lifted. Radiological criteria for the implementation of long term actions are given in the BSS [2] and have been further developed by the ICRP [29].

Monitoring may also be necessary for the purpose of special investigations into the behaviour of particular radionuclides in the environment, such as the investigation of the effectiveness of particular countermeasures or in order to make use of the opportunity to develop information on transfer coefficients. Nevertheless, once the countermeasures have been lifted, the environmental monitoring programme can be reduced progressively.

5.5. INDIVIDUAL MONITORING

Individual monitoring includes measurements of external dose by equipment worn by an individual or measurements of quantities of radioactive materials in or on their bodies, the ultimate objective of individual monitoring being the estimation of doses [1]. In planned exposure situations, individual monitoring is used to assess the doses to workers and it is most unusual for such monitoring of members of the public to be carried out in non-emergency situations. Individual monitoring may, however, be undertaken for the purpose of

special investigations, but even then, it is unlikely that it would be for an extended period of time.

There might be more justification for individual monitoring for the assessment of dose to an individual in the event of an accident. But even then, it is likely to be rare. It might, however, be necessary for the following reasons:

(a) To verify the dose assessments that have been made;
(b) To reassure individuals;
(c) To provide information to assist in decisions regarding whether to undertake action to reduce a person's dose from radionuclides incorporated within the body;
(d) For the purposes of long term medical follow-up;
(e) For the purposes of a research programme.

5.5.1. Monitoring of external dose

Individual monitoring of the external dose due to gamma and/or neutron radiation under non-accidental conditions is not recommended. The source and environmental monitoring programmes should be sufficient for the purposes of determining the doses from external radiation to the representative person. As indicated in the previous section, individual monitoring is also likely to be rare in the event of an accidental release of radioactive material. If it is used for any reason, film badges, TLDs or electronic dosimeters would be appropriate. Film is less satisfactory for use in the general environment, because of its energy dependence, fading and sensitivity to environmental conditions. It should also be noted that the interpretation of any measurement may be difficult because the dose may fall within the range of the variation of the natural radiation background.

5.5.2. Monitoring of internal exposure

In the case of an accidental release of radioiodine, measurements of iodine isotopes in the thyroid should be made as soon as possible. Monitoring of radioiodine content in thyroid glands should be undertaken with an appropriately collimated and calibrated gamma detector. The measurements will provide input information for the assessment of the committed dose and may help to reassure members of the public, for example, those who have been evacuated. In addition, they should provide information on whether longer term medical follow-up will be necessary. It is noted, however, that once radioactive isotopes of iodine have been taken up by the thyroid, iodine prophylaxis with stable iodine is not effective in removing it.

The direct measurement of other gamma emitting radionuclides such as cobalt-60 and radioisotopes of caesium incorporated within the body may be made by whole body counters (WBCs), partial or scanning body counters (Fig. 13). Caesium distributes throughout the body relatively uniformly. Whole body counting utilizing adequate levels of shielding should be used for monitoring the radioactive isotopes of this element. For particulate material that has been inhaled, monitoring of the lungs would be appropriate. The IAEA has published two relevant recommended procedures, entitled "Direct Methods for Measuring Radionuclides in the Human Body" [152] and "Rapid Monitoring of Large Groups of Internally Contaminated People Following a Radiation Accident" [153]. These procedures should be adopted when monitoring members of the public is considered necessary.

The doses due to incorporated beta emitters, such as tritium, iron-55 and strontium-90, and most of the alpha emitters, such as radium-226, and isotopes of thorium, uranium and plutonium, are usually estimated by bioassay. Metabolic models are needed for the interpretation of the measured data. Appropriate information is contained in a number of sources, including the IAEA guide on "Assessment of Occupational Exposure Due to Intakes of Radionuclides", in which sampling methods, biokinetic models for internal dosimetry and the interpretation of measurements are described [27].

A streamlined approach to the interpretation of bioassay data and retrospective dose assessments is proposed in Refs [30, 154, 155]. The approach anticipates use of the reference dose coefficients 'dose per unit measured value' or 'dose per unit content' in the one-step dose assessments. The source, environmental or individual monitoring data, such as measured discharge levels, time-integrated concentrations of radionuclides in the breathing zone, WBC or bioassay data, could be used as input information for such assessments. The ICRP indicates that there can be advantages in calculating the dose directly from the measurements using the tabulated in advance functions that relate doses to the parameters of exposure and to the measured quantities [30]. Particularly, the ICRP plans to publish tables of 'dose per unit radionuclide content' values in the body as a function of time after the radionuclide intake. This will aid the prompt dose assessments by ensuring that reference models are used and will limit the opportunity to make errors in the complex chain calculations [30].

A comprehensive review of computer codes for the interpretation of bioassay data is given in Ref. [156].

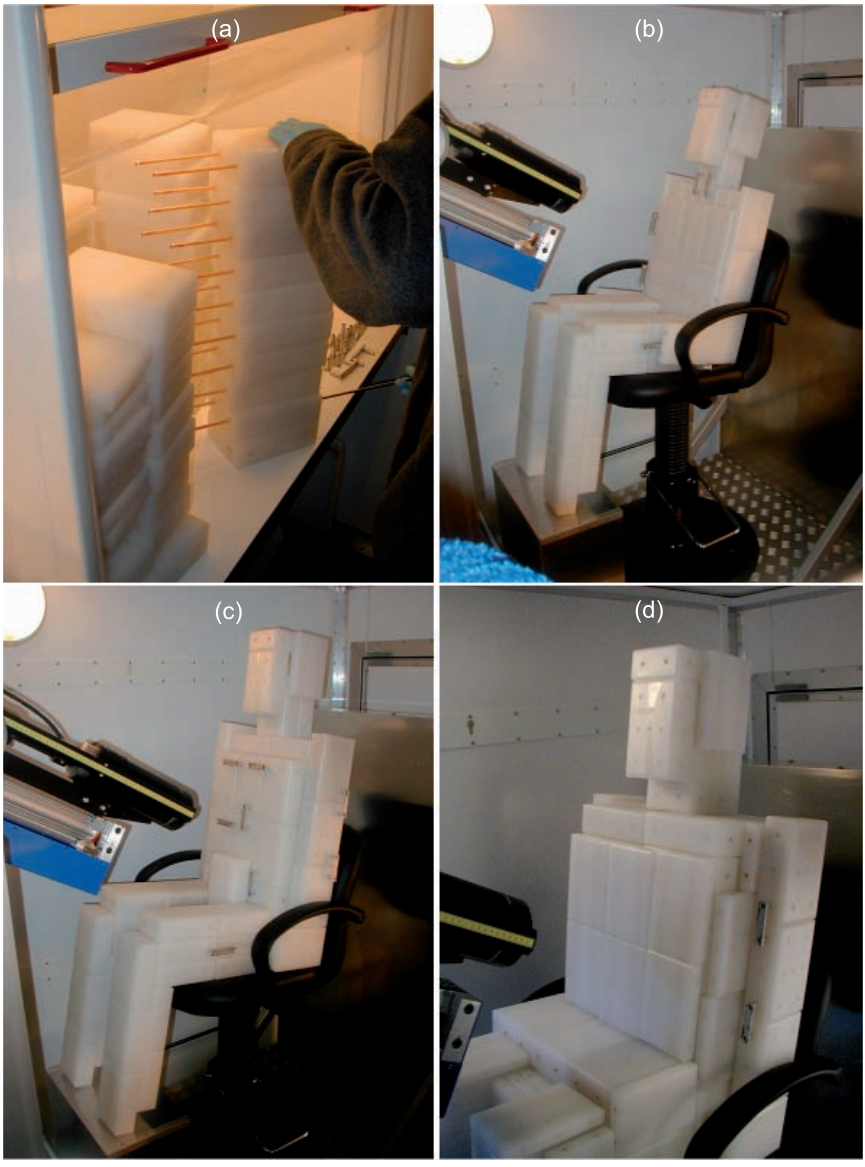

FIG. 13. Whole body HPGe counting for measurement of incorporated gamma emitting radionuclides: (a) preparation of tissue equivalent calibration elements; (b, c, d) calibration phantoms: (b) child; (c) medium male; (d) heavy male. (Source: NRPA.)

6. GENERIC ASPECTS OF MONITORING PROGRAMMES

6.1. SAMPLING

Both source and environmental monitoring programmes involve taking and measuring samples. Most of the data on the discharge of radionuclides from nuclear facilities are usually obtained using on-line measurement systems. Sampling and subsequent measurements of radionuclide activities in either discharged air or water are most often used to determine the radionuclide composition of a discharge or, in cases where the activity of a discharge is low, on-line methods may not be sufficiently sensitive. For environmental programmes, sampling and measurement are the primary means of proving compliance with the established limits for levels of radionuclides in environmental media and for providing data for dose assessment. In an emergency situation, information relating to the source is most likely to be drawn from on-line systems and sampling will be primarily confined to air sampling and sampling of environmental media for the determination of deposition and to contribute to dose assessments.

6.2. LABORATORY SAMPLE ANALYSIS

Both source and environmental monitoring programmes involve laboratory measurements of samples. Laboratory analysis of samples taken as part of the monitoring programme serves to measure analytes that cannot be measured by in situ or on-line means in a manner that satisfies the requirements of the monitoring programme or that demonstrates dose constraint compliance. Laboratory analyses may also serve to ensure that in situ or other measurement systems are providing accurate and reproducible data. The laboratory analysis of monitoring samples should be conducted within an appropriate quality management system such that data generated as part of the monitoring programme are traceable, accurate, representative, reproducible and defensible.

Typical radioanalytical laboratories will be equipped with instrumentation appropriate for the analytes that may be encountered as part of the monitoring programme and will usually feature some or all of the following instruments:

(a) Gas proportional detectors for alpha and beta counting;
(b) Scintillation counters (NaI, LaBr, etc.) or HPGe gamma spectrometers for qualitative and quantitative analysis of gamma emitting radionuclides;
(c) Low energy gamma or X ray detectors;

(d) Solid state detectors for alpha spectrometric measurements;
(e) Liquid scintillation counters for measurement of both alpha and beta emitting radionuclides;
(f) Mass spectrometers.

Methods used in the laboratory analysis of samples should be those described in standard texts or as provided by national or international authorities. The performance of laboratory based radioanalytical procedures should be assessed in terms of accuracy and precision by regular participation in national and international intercomparisons and the use of unannounced spikes and blanks to the sample stream. Laboratory analyses should be conducted according to internationally accepted standard methods and, where methods are not standard methods, full validation of the implemented method should be conducted within the laboratories' quality management system. Appropriate compendia of radioanalytical methods can be found in Refs [82, 83, 116, 117, 157] or within the publications of organizations such as the National Council on Radiation Protection and Measurements (NCRP), the American National Standards Institute (ANSI), the American Society of Testing and Materials (ASTM), the Association française de normalisation (AFNOR), the United States Environmental Protection Agency (EPA), the US Department of Energy (DOE) and the IAEA (see Bibliography).

6.3. DETECTION LIMITS AND UNCERTAINTIES

The detection limits have to be adequate to achieve the objectives of source and environmental monitoring. This means that the detection limits for routine releases have to be low enough that compliance with the authorized limits can be safely demonstrated, data on annual releases can be provided and exposure to the representative person can be assessed. For the practical derivation of detection limits, parameters of interest are the:

(a) Instrument background count rate;
(b) Efficiency of the counting system;
(c) Efficiency of the sampling system;
(d) Discharge flow rate;
(e) Sampling flow rate;
(f) Sampling period;
(g) Counting time.

The lower detection limit for on-line source monitoring may be, as an example, less than 1% of discharge limits to adequately cover the releases of each radionuclide group and to demonstrate compliance with discharge limits. The detection limits of on-line systems should be at least one order of magnitude lower than the investigation levels. Full and thorough introduction and discussion of the concept of detection limits in relation to source and environmental monitoring of radioactivity can be found in Refs [158–163]. An overview of measurement equipment for source monitoring is given in Appendix III, including detection limits of different measurement systems.

Uncertainties are associated with measurements and the estimation of doses from those measurements and associated models. Measurements of radionuclide activity, absorbed dose and personal, ambient or other dose equivalents will have associated uncertainties, which should be quantifiable, including the calibration of the instruments used to make the measurements. Sampling uncertainties will be associated with the limited amount of material sampled in the discharges and in the environment, and in the selected locations and times for dose and dose rate measurements. In addition, the sampling locations themselves may well not be representative of the quantity that needs to be assessed, such as the dose to the representative person.

Modelling or mechanistic uncertainties arise through the inevitable use of numerical or mathematical models to represent physical, biological and environmental processes. The models themselves may be simplified representations, or the parameters used in the models may not be totally appropriate. For example, estimates of the intake of food by the representative person and their other habits will be subject to physiological variability. Furthermore, the actual behaviour of radionuclides within the body will depend on the physiological nature of the exposed individuals.

Conceptual uncertainties arise from incomplete knowledge of the exposure conditions, for example, where some significant exposure pathway or mechanism has been overlooked.

In most cases, formal numerical treatments are not applied to modelling due to complexity, for example, Ref. [164]. Any uncertainty will usually be a rough estimation but this does not make such estimates valueless provided they are based on genuine and realistic evaluations.

In monitoring the discharges and the environment, the focus should be on the uncertainties involved in the actual sampling and measurements themselves. Any reports giving the results of source and environmental monitoring

programmes should, therefore, address these uncertainties. Measurement uncertainties should be evaluated, promulgated, combined and expressed in appropriate statistical terms based on the guidance given in Ref. [165] or other standard textual references on measurement statistics[12]. Without such an indication, measurement results cannot be compared, either among themselves or with reference values given in regulations or other standards. Uncertainties should be expressed in standard format — an arithmetic or geometric standard deviation — or with the half-width of an interval having a stated level of confidence, that is, a confidence level, which normally is 95%. The standard uncertainty should include statistical (e.g. counting) and experimental (measurement) components as well as any estimates due to sampling or other aspects [165]. If the uncertainty expressed contains only some of these components, this should be stated clearly. If Monte Carlo methods are used rather than classical statistical analysis [166], sufficient detail of the methodology must be made transparent.

To avoid loss of information due to rounding errors, raw data should not be rounded or substituted by 'less than' values, rather, original numbers should be used in information processing. Final reported numerical values, however, should not be given with more significant figures than the total uncertainty warrants. Further authoritative information as to the handling of uncertainties in the monitoring of radioactivity can be found in Refs [95, 167–169].

Appropriate statistical analysis of data obtained as part of a monitoring programme should be conducted such that, as a minimum, a measure of both the trueness and precision of the result is obtained. The repeatability and reproducibility of the measurements made by instruments and methods used in accruing monitoring data should be determined. Appropriate statistics should be employed at all stages of the monitoring programme to ensure that generated data are of a quality that can demonstrably satisfy the purposes of the programme and that patterns, trends and associations can be observed with stated levels of confidence. Full and thorough discussion of the application of appropriate statistics in this regard can be found in Refs [170–176] or elsewhere (see Bibliography).

[12] The formal definition of uncertainty of measurement given in Ref. [165] is 'parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand' (i.e. the measured value).

6.4. QUALITY MANAGEMENT SYSTEMS

The establishment of a quality assurance programme[13] is a requirement of the BSS [2]. Additionally, accreditation of the quality management system for laboratories is advisable. These programmes are required to provide, as appropriate:

(a) Adequate assurance that the specified requirements relating to protection and safety are satisfied;
(b) Quality control mechanisms and procedures for reviewing and assessing the overall effectiveness of protection and safety measures.

Thus, as a minimum, the quality assurance programme should be designed to satisfy the requirements established by the regulatory body. More than this, it reflects the commitment of the registrant or licensee and designated agencies to their responsibility for the proper management of safety.

The IAEA Safety Standard on the Management System for Facilities and Activities, IAEA Safety Standards Series No. GS-R-3 [177], requires a management system to be established, implemented, assessed and continually improved, the main aim of which is required to achieve and enhance safety by:

(a) Bringing together in a coherent manner all the requirements for managing the organization;
(b) Describing the planned and systematic actions necessary to provide adequate confidence that all these requiremelnts are satisfied;
(c) Ensuring that health, environmental, security, quality and economic requirements are not considered separately from safety requirements, to help preclude their possible negative impact on safety.

As such, quality assurance should be an integral part of all monitoring programmes [10]. In the specific context of monitoring programmes, its purpose is to provide a disciplined approach to monitoring, in order to provide confidence in the results of both the measurements and the dose estimations that rely upon them. This means that steps should be taken to ensure quality in every part of the monitoring programmes, including:

[13] Within this report, the usage of the terms ‘quality management system’, ‘quality assurance’ and ‘quality control’ is the same as that found in the BSS [2].

(a) Design and implementation of monitoring programmes (selection of suitable equipment, sampling locations and procedures);
(b) Maintenance, testing and calibration of equipment and instruments;
(c) Use of calibration standards;
(d) The quality control mechanism and procedures for reviewing and assessing the overall effectiveness of the monitoring programme;
(e) Uncertainty analysis;
(f) Record keeping;
(g) Qualification and training of personnel.

An essential requirement of all management systems is that they should be documented. Thus, all of these components should be written down in a form that is understandable to those who are involved in the monitoring programmes. They should also be available for review by the regulatory body concerned with the authorization of discharges to the environment, since the regulatory body would clearly be concerned about the quality of the information obtained by the authorized person from source and environmental monitoring programmes.

Reference [177] requires the management system itself to be monitored and measured to confirm the ability of the processes to achieve the intended results and to identify opportunities for improvement. As such, each component of the monitoring programmes should be routinely checked and evaluated to ensure that the appropriate procedures are correctly implemented, that the measurements are reliable, and that the data analyses and dose assessments are appropriately carried out. Both self-assessment by the management and independent assessment of the effectiveness of the management system are required to be carried out [177]. Weaknesses, obstacles, causes of non-conformance and opportunities for improvement are required to be identified and actions to improve the processes selected, planned, performed and recorded. Guidance on the Application of the Management System for Facilities and Activities is given in IAEA Safety Standards Series No. GS-G-3.1 [178].

For certain facilities, independent external verification of quality assurance systems may be required. Even if it is not explicitly required, it may well be desirable. Certification to, or adoption of, an appropriate standard of the International Organization for Standardization (ISO) should be considered. The ISO Standard on Quality Management Systems: Requirements (ISO 9001) [179] deals with management systems in general; the ISO Standard on Environmental Management Systems: Specification with Guidance for Use (ISO 14001) [180] covers more specifically the environmental issues. The appropriate standard for accreditation testing laboratories is ISO/IEC 17025 [181]. The management, performance and appraisal elements of quality assurance programmes related to the surveillance and monitoring of near surface disposal facilities for radioactive

waste are presented in Ref. [16]. These elements are generally applicable to all source and environmental monitoring programmes.

6.4.1. Quality assurance in source monitoring

Source monitoring may include on-line monitoring, continuous monitoring with periodic collection and analysis of sample media, and collection and analyses of periodic short term samples, such as batch sampling of liquid discharges. Regardless of the type of monitoring used, collection of a representative sample of the discharge to the environment is the essential first step in the monitoring process.

Systems for reliable delivery and collection of representative samples of airborne discharges may require several stages of development. In the pre-operational phase, the design of the sample extraction system should be documented, and the proposed system should be independently reviewed by the regulatory body. Prior to installation, thorough mixing of the discharge at the sampling location should be confirmed through the performance of appropriate tests, which should be documented. Proper installation, including testing for leakage and any needed heat tracing of the sampling system, should be confirmed and documented. Estimates of losses during sample extraction and transport should be made; the basis for appropriate correction factors should be documented by the operator and reviewed by the regulatory body.

During the operational stage, leak testing should be performed periodically to ensure continued integrity of the sampling system. The functioning of the heat tracing (if needed to avoid condensation) should also be checked routinely (or automatically) and documented.

The performance of air sample collection media, which should have been selected carefully on the basis of the expected discharge composition (radionuclides, and their particle sizes and chemical forms), should be tested periodically. This can frequently be accomplished using the normal facility discharge by operating two filters (or charcoal cartridges or other collectors) in series and comparing the activities accumulated on the first and second collectors.

To provide assurance that no confusion over the origin of samples or no tampering of the samples has occurred, procedures for sample collection should define a unique labelling process and the steps required to record the chain of custody of the samples. Generally, more complex procedures will be required for licensed than for registered facilities, and in cases when samples are sent to an off-site laboratory for radiochemical analysis. Procedures for sample analyses should be reviewed to ensure that the unique label is always associated with the sample, aliquots of the sample, and processed components of the sample. Records

of the transfer of samples should be reviewed periodically to ensure that the procedure for the chain of custody has been followed and that there was no opportunity for tampering with the samples.

Because they are essential to the accurate estimation of releases, the systems used to measure discharge and sampling flow rates should also be covered by the quality assurance programme. Changes in airborne discharge flow rates may occur from time to time, and these should be recorded. Calibrations of air and liquid flow meters should be routinely performed and documented, and should be traceable to national or international standards. These records should be reviewed to ensure that the proper discharge and sampling flow rates were used in calculations of releases.

A programme of routine checks of the operability of the sampling system, daily or automatic, is important to ensure that sampling systems will meet established goals for operational performance. Recording data from sampler run time meters will provide positive information about the operation of the system. For systems with high reliability requirements, failure alarms should be incorporated. Preventative maintenance programmes for the sampling systems are also important for achieving a high percentage of operability. The ready availability of spare equipment will also help to minimize downtime of the sampling systems.

6.4.2. Calibration and control of equipment

To ensure that measurement results are reliable, it is essential that all instruments used to measure radionuclide activity, either on-line or in samples, be regularly calibrated using a source traceable to a national or international standard. Included among these instruments are field gamma spectrometry systems, portable exposure rate meters, and perhaps also fixed exposure rate measurement systems. The calibrations should be carried out by an appropriately accredited laboratory. The operator is responsible for review of the instrument calibration information and for ensuring that each instrument is calibrated according to the prescribed schedule.

The calibration data and any changes in instrument calibration factors or detection efficiencies should be carefully documented and saved, to provide a history of the operation of the instrument.

Calibration of high range monitors that would be used in emergency conditions at licensed facilities may be particularly challenging. Any deviations of the system from linear response should be noted and documented. The regulatory body should review the calibration data to ensure that the dynamic range required for emergency monitoring can be achieved. To ensure that

post-accident samples can be safely retrieved, a thorough analysis should be performed in advance and submitted to the regulatory body for review.

Independent review of the instrument calibration records should be performed routinely by the operator and periodically by the regulatory body.

Routine checks for operability and measurements of background counting rates should also be performed. This may require the use of check sources. Such checking is, however, not a substitute for regular calibration. The results of routine checks should be recorded in a logbook or other permanent file for the instrument. Appropriate specific discussion pertaining to the calibration of instrumentation can be found in a range of sources, including for HPGe detectors [182, 183], scintillation counters (gamma) [184], alpha/beta proportional counters [185], liquid scintillation counters [186] and general radiation protection instrumentation [187–189].

6.4.3. Quality in radioanalytical procedures

An effective laboratory quality management system would normally incorporate the aspects described in this discussion. The laboratory of the operator or of the organization employed to perform radiochemical analyses should meet the national standards for such analyses:

(a) Proficiency tests and other laboratory intercomparisons;
(b) Blank samples to ensure that there is no unexpected source of activity in reagents or cross-contamination of samples processed in parallel;
(c) Analysis of reference materials;
(d) Analysis of duplicate samples;
(e) Accreditation by an appropriate accreditation body.

Use of duplicate samples and reference materials would normally be part of the standard practice of the laboratory. Unannounced use of reference materials and duplicates may be used as an independent check of the laboratory quality system, especially for the use of external contracting laboratories.

6.4.4. Quality in the counting of samples

The instruments used to measure activity at a particular facility will depend upon the regulatory requirements and the complexity of the monitoring tasks. On-line airborne or liquid activity monitors, alpha, beta and gamma spectrometry systems, gross alpha or beta activity counters of various types, and liquid scintillation detectors may be employed, depending on the requirements. Instrumentation needs for registered facilities are not likely to be as extensive as

for licensed facilities, but the quality assurance process for the instruments that are used is just as important.

To ensure that instrumental outputs (e.g. radioactivity counting results) have been interpreted properly and concentrations calculated appropriately, both the raw data and calculations should be routinely checked. Therefore, when the radioactivity in intact samples, or in the appropriately prepared fraction from sample processing, is measured, the relevant data (instrument used, gross counting rate, background counting rate, counting time, counting efficiency, volume of air or water in the original sample) should be recorded and retained. For spectrometric measurements, the energy calibration, peak identification and background subtraction processes should be similarly documented and saved. Methods used to estimate the uncertainty associated with measurement results or to compute minimum detectable levels for the measurements should be clearly shown in the sample analysis record. The review and checking of the analytical data and calculations should be documented.

Appropriate correction methods should be implemented where necessary. Examples of such corrections include matrix, decay/ingrowth and coincidence summation corrections for gamma spectrometry. Where applied, such corrections should be fully documented and their contribution to the overall uncertainty budget calculated.

To ensure that the counting systems will continue to perform efficiently, periodic preventative maintenance should be scheduled, performed and documented. Any modifications of the counting systems should also be documented when they are introduced. Routine source checks and background determinations should be scrutinized after any modification. Instrumentation should be operated in environments such that the potential for interferences is minimized. Particular attention should be paid to temperature effects on detector responses, background reduction via either passive or active methods, electrical interferences, etc. Useful presentation of aspects pertinent to the operation of radioanalytical instrumentation as part of monitoring programmes can be found in Ref. [190].

6.4.5. Record keeping

Appendix III of the BSS [2] requires authorized persons to keep appropriate records of the results of the monitoring programmes. As indicated in the previous section and in IAEA Safety Standards Series No. GS-R-3 [6], this is a key element of the management system of which the quality assurance of the environmental monitoring programme is a part.

IAEA Safety Standards Series No. RS-G-1.8 provides guidance on the data that should be recorded [10]. The data from source monitoring that should be recorded include the dose rate due to direct radiation during the reporting period, and the composition, rates and total amount of annual discharges. These data along with information on discharge points, sampling periods, radioanalytical procedures and instruments used, as well as instrument calibration, should be maintained.

The same Safety Guide cited previously [10] also recommends that the data from environmental monitoring, covering the environmental radiation levels and radionuclide concentrations around the facility, should be recorded. The record keeping system should be designed to retain all relevant information about the collection of individual samples, measurements of samples, calibration procedures and uncertainties, as well as summaries of the results that are reported routinely. It should document the sample collection process, sampling location, time period of sampling, medium used and sample number, as well as the detailed radiological information. An appropriate set of guidelines on the reporting of analytical data generated from environmental samples can be found in Ref. [191].

Arrangements for recording and reporting results are stated in IAEA Safety Standards Series No. RS-G-1.8 [10].

The recording and reporting of monitoring results and related information should satisfy the objectives of the monitoring programme, which include the requirement to calculate the annual dose to the representative person, or at least to carry out a comparison of measured values with appropriate derived levels[14]. Interpretation of the results of monitoring is taken to be an integral part of the monitoring programme itself.

The BSS [2] requires the registrants and licensees to, if appropriate:

(a) Record the monitoring results and estimate any exposures;
(b) Keep appropriate records of the results of the monitoring programmes;
(c) Report a summary of the monitoring results to the regulatory body at approved intervals;
(d) Report promptly to the regulatory body any significant increase in environmental radiation fields or contamination that could be attributed to the radiation or radioactive releases emitted by sources under their responsibility;
(e) Report any releases exceeding the authorized discharge limits in accordance with the criteria established by the regulatory body.

[14] See footnote 9.

All the results of the laboratory measurements have to be compiled. In order to allow auditing of the monitoring data, it is necessary that records be kept of all relevant intermediate results obtained in the course of analysis and of the parameters used for the calculation of the reported data. Records of any investigations regarding unusual environmental occurrences should also be kept.

The data in the records of the source and environmental monitoring programme should be scrutinized periodically to determine any trends that may have occurred. They also should be used to check any calculations used in the assessment of the movement of radionuclides in the environment.

The records should be retained, as a minimum, for at least the period of time specified by the regulatory body or in regulatory documents. In practice, the period will usually be for at least the period of the validity of the authorization plus any decommissioning period and for 30 years subsequent to that.

7. DOSE ASSESSMENT, DEMONSTRATION OF COMPLIANCE WITH RADIOLOGICAL CRITERIA AND REPORTING TO THE REGULATORY BODY

Appendix III of the BSS requires the registrants and licensees to be responsible for the establishment, implementation and maintenance of measures for ensuring the optimization of protection of members of the public whose exposure is attributable to the sources under their responsibility. In the optimization of protection, the authorized person is required to take account of the dose constraints established by the regulatory body. Appendix III of the BSS also requires measures to be taken for ensuring the limitation of the exposure of the representative person[15], which is attributable to such sources. The selection of the representative person should take account of present and future generations, whether in the countries where the sources are located or in any other country or place.

The BSS explicitly requires the registrant and licensee, prior to discharging radioactive material to the environment, to assess prospectively the doses to the representative person due to the planned discharges. At the operational stage, the doses to the representative person should be assessed retrospectively with the use of the source and environmental monitoring data.

[15] See footnote 2.

The degree of detail associated with such dose assessments will depend, however, on the potential hazard presented by the facility. The IAEA developed procedures and models for the purpose of screening assessments [14]. Such screening models are intended to assist in determining the likely magnitude of the impact of the proposed discharge and, hence, whether it can be removed from further consideration or whether more detailed analysis is necessary. The models are expected to be particularly useful for assessing the radiological impact of discharges from small scale facilities such as hospitals or research laboratories[16]. For such facilities, following an initial review of the possible exposure pathways and possible doses to the representative person, it may be sufficient during operation just to demonstrate that the discharge rates are within the authorized limits. This would make the development of special local arrangements for dose assessment unlikely to be warranted.

It should be noted that, since the screening models are designed to be conservative, they will overestimate the actual doses received by the representative person. Specific guidance on assessments of doses to the public is given in Safety Reports Series No. 14 [13].

Major pathways of radionuclides to humans for environmental dose assessment models are given in Appendix IV. A fuller description of the models is given in Safety Reports Series No. 19 [14]. A substantial set of radionuclide transfer parameters for the terrestrial and freshwater environment can be found in Technical Reports Series No. 364 [192][17]. Further details of dose assessments are given in Appendices IV, V and in Refs [18, 193–196].

Comprehensive assessments of doses to the representative person due to releases will, in general, be necessary for nuclear facilities in planned, existing and emergency exposure situations. Doses should be assessed for releases of radionuclides to air and water, taking into account all relevant exposure pathways, as well as direct radiation from the source. Assessors are likely, therefore, to need to follow a calculation with a more realistic site specific and detailed assessment. Furthermore, comprehensive monitoring would be needed which, according to the BSS [2], should be sufficient to enable the exposures of the representative person to be estimated. This is especially necessary in

[16] It should be noted that the modelling approaches described in Safety Reports Series No. 19 [14] are applicable to continuous or prolonged releases into the environment when it is reasonable to assume that an equilibrium or quasi-equilibrium has been established with respect to the released radionuclides and the relevant components of the environment. They do not apply to instantaneous or short-period releases such as might occur in an uncontrolled or accident situation.

[17] The updated technical report is in preparation.

emergency and existing exposure situations or when the calculated doses are close to the authorized limits in planned exposure situations.

In general, the results of environmental monitoring (e.g. data on external radiation and radionuclide activities in air, soil and food) can be used to check and improve the dose assessments. It may even be useful to measure site specific radioecological parameters and to verify the habits of the population, for example, food consumption and occupation habits.

All results from monitoring measurements, whether carried out by the registrants or licensees, by an independent measuring laboratory or by a designated organization, should be made available to the regulatory body along with relevant supporting information [2].

In planned exposure situations, the results from on-line monitoring should be summarized and presented in a way that allows the regulatory body to make a judgement on the performance of the discharge treatment and control systems.

The reports of registrants and licensees to the regulatory body should contain:

(a) An overview of the monitoring programme;
(b) Annual releases of radionuclides to air and water;
(c) Annual results of the measurement of direct radiation from the source;
(d) Activity concentration in environmental samples such as air, precipitation, water, soil and indicators;
(e) Measured activities in foodstuffs, where appropriate;
(f) Comments on significant changes from measurement results which had been obtained in preceding years;
(g) Results of calculations of doses to members of the public due to annual releases of radionuclides to air and water;
(h) Comparison of the released activities and doses with authorized limits;
(i) Remarks on elevated releases, if such occurred.
(j) Volume of discharged air and water during the reporting period;
(k) Total activity discharged during the reporting period;
(l) Sampling times, sampling volume, etc.;
(m) Comparison of the discharged activities with authorized discharge limits.

Essential information to be recorded and, where appropriate, reported, includes:

(a) Sampling locations which should be clearly indicated, for example, on a map;
(b) Date or period of sampling;

(c) A comparison of results with the data obtained prior to the facility going into operation, and with the results from previous years;
(d) An explanation of any deviations in the activity levels.

The models used in the assessment of dose should be included. It is useful to compare the results from dose calculations with those from environmental monitoring. A statement on the agreement of measurements and calculations is appropriate.

The regulatory body and/or the registrants or licensees should make available to the public a report with a summary of the monitoring programme and the results of dose assessments.

Appendix I

SUMMARY OF THE RECOMMENDED SCOPE OF ROUTINE MONITORING PROGRAMMES FOR DIFFERENT FACILITIES

The type of source and environmental monitoring programmes, as well as their scale and extent, should be commensurate with the nature of the source characteristics at the expected or current discharge rates, the radionuclide composition, the comparative significance of different exposure pathways, and the magnitudes of expected and potential doses to individuals [10].

Source and environmental monitoring is not required for practices and sources that have been exempted by the regulatory body, since exemption should be based on the radiation risks to individuals and populations being so low as to be of no regulatory concern, and the practices and sources are inherently safe.

I.1. SOURCE MONITORING

Source monitoring is required for all other practices discharging radioactive material to the environment. This applies particularly to licensed facilities. This appendix develops the guidance given in this Safety Guide and provides an overview of the types of monitoring required for different types of facilities, and of the responsibilities for source and environmental monitoring.

A summary of the types of source monitoring programmes that might be implemented for different types of practice is given in Table 3 with more detailed elaboration provided in Table 4. A distinction is made between licensed and registered facilities. This distinction is intended to indicate the graded approach that should be applied, rather than the actual distinction that is made in countries between licensed and registered facilities. Some countries, for example, require all non-exempt practices to be licensed, although the requirements of licences will vary according to the risks presented by the facilities.

I.2. ENVIRONMENTAL MONITORING

Routine environmental monitoring is necessary when significant releases of radioactive material could be anticipated. The majority of facilities from which such releases may be anticipated will be part of the nuclear fuel cycle. A summary of the types of environmental monitoring programmes that might be implemented for different types of nuclear facilities is given in Table 5.

TABLE 3. TYPES OF MONITORING AND DOSE ASSESSMENT REQUIRED FOR DIFFERENT TYPES OF SOURCE

		Type of monitoring			
Exposure category	Type of source	Source monitoring	Environmental monitoring	Individual monitoring	Dose assessment
	Excluded exposures; exempted, cleared sources	No monitoring required			
Planned exposure situations	Registered source	Required	Not required		
	Licensed source	Required		Not required	Required
	Multiple licensed sources	Required	Required	Not required	As appropriate
Existing exposure situations	Chronic (prolonged exposure situation)	As appropriate	Required	As appropriate	As appropriate
Emergency exposure situations	Emergency situation	Required	Required	As appropriate	Required

Environmental monitoring programmes should enable the results of the source monitoring programme to be verified. The objectives of environmental monitoring programmes may vary with the stage of operation. In the pre-operational stage, monitoring is designed to establish the existing levels of radionuclides and dose rates in the environment, elucidate local factors (i.e. meteorology, hydrology, population distribution, land use) that will affect doses, and establish the monitoring network and environmental sampling programmes necessary for ensuring regulatory compliance. In the early stages of operation, frequent and detailed measurements will be required to confirm the predictions of the behaviour and transfer of radionuclides in the environment. As experience is gained, it might be possible to reduce the scale of the environmental monitoring programme.

TABLE 4. TYPES OF POSSIBLE SOURCE MONITORING PROGRAMMES

Source			Licensed facilities (examples)												Hospitals	
			Nuclear power plants		Fuel fabrication or enrichment plants		Reprocessing plants		Waste management facilities and final repositories		Research reactors		Radio-pharmaceutical facilities			
			On-line	Off-line	On-line	Off-line	On-line	Off-line	On-line	Off-line	On-line	Off-line	On-line	Off-line	On-line	Off-line
Airborne discharges	Noble gases		+	(+)	–	–	+	–	–	–	+	(+)	–	–	–	–
	Aerosol	β/γ	+	–	(+)	+	+	+	+	+	(+)	+	+	+	(+)*	(+)*
		β	–	(+)	(+)	+	+	+	(+)	(+)	–	(+)	(+)	(+)	–	(+)*
		α	–	(+)	–	+	+	+	–	+	–	–	–	+*	–	–
	Other gases and volatiles	^{131}I	(+)	(+)	–	–	+	+	–	–	(+)	+	+*	+*	(+)*	+*
		^{129}I	–	(+)	–	–	–	+	–	+	(+)	+	+*	+*	(+)*	+*
		Tritium	–	(+)	–	–	–	+	–	–	–	(+)	–	+*	–	–
		Carbon-14	–	(+)	–	–	–	+	–	(+)	–	(+)	–	+*	–	–

TABLE 4. TYPES OF POSSIBLE SOURCE MONITORING PROGRAMMES (cont.)

Source		Licensed facilities (examples)												Hospitals	
		Nuclear power plants		Fuel fabrication or enrichment plants		Reprocessing plants		Waste management facilities and final repositories		Research reactors		Radio-pharmaceutical facilities			
		On-line	Off-line	On-line	Off-line	On-line	Off-line	On-line	Off-line	On-line	Off-line	On-line	Off-line	On-line	Off-line
Liquid discharges	β/γ	(+)	+	–	(+)	+	+	+	+	(+)	+	+	+	–	+*
	β	–	+	–	–	–	+	–	+	–	+	(+)	+	–	+*
	α	–	+	–	+	–	+	–	+	–	+	–	–	–	–
	Tritium	–	+	–	–	–	+	–	+	–	+	(+)*	+*	–	–
Direct radiation	γ	(+)	+	–	+	–	+	–	+	(+)	+	–	–	–	+*
	n	–	(+)	–	+	–	+	–	–	–	(+)	–	–	–	–

\+ Necessary.
(+) Recommended for consideration.
– Not recommended or necessary, or not practicable.
* Depending on the characteristic of the radionuclides that are used.

TABLE 5. TYPES OF POSSIBLE ROUTINE ENVIRONMENTAL MONITORING FOR NUCLEAR FACILITIES

	Nuclear power plants	Fuel fabrication or enrichment plants	Reprocessing plants	Waste management facilities and final repositories
External radiation				
Gamma dose rate	+	+	+	+
n-dose rate	–	+	+	(+)
Air				
Aerosols	+	+	+	+
Gases	+	+	+	(+)
Food and feedstuffs				
Leafy vegetables	+	+	+	+
Other vegetables and fruits	+	(+)	+	+
Drinking water	+	(+)	+	+
Milk	+	(+)	+	+
Grain	+	(+)	+	+
Meat, game	+	(+)	+	+
Terrestrial media and indicators				
Grass	+	+	+	+
Soil	+	–	+	+
Lichen, mosses	+	–	+	+
Aquatic media and indicators				
Water	+	(+)	+	+
Sediment	+	(+)	+	+
Fish	+	(+)	+	+
Shellfish	+	(+)	+	+
Seaweed	+	–	+	+
Benthic animals	+	–	+	+

\+ Recommended.
(+) For consideration.
– Not recommended or not necessary, or not practicable.

Although many operations do not lead to readily detectable levels of radionuclides in the environment either in the early stage of operation or after years of operation, the decision to reduce the frequency of sampling or the scope of the environmental monitoring programme must be reviewed carefully, taking into account concerns raised by the public. Environmental monitoring also has the potential to detect both routine releases and any abnormal releases which otherwise may not have been detected, therefore, maintenance of the monitoring may be desirable to detect abnormal releases.

Environmental monitoring programmes may include both radionuclide specific measurements (by means of spectrometry or radiochemical analysis) and gross alpha and gross beta activity measurements. Gross activity measurements, however, do not provide information on which dose assessments can be made. Furthermore, they will include the contributions from any radionuclides that are already in the environment, such as potassium-40 in the case of gross beta measurements, which may predominate. Radionuclide specific measurements, therefore, are necessary for the purposes of dose assessment.

The main advantage of the measurements of gross activity is that they are relatively inexpensive and straightforward, so a large number of them may be included in an environmental monitoring programme. They should be used to warn of any unexpected situation and should be periodically supplemented with radionuclide specific measurements. Any significant fluctuation in the results of the measurements of gross activity should trigger further investigation, including radionuclide specific measurements. For this reason, monitoring programmes should include predefined gross beta and gross alpha levels (i.e. investigation levels) and predefined procedures, which automatically trigger radionuclide specific measurements.

Bearing in mind the previous discussion of monitoring environmental matrices, 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.

I.3. SOURCE AND ENVIRONMENTAL MONITORING PROGRAMMES FOR NUCLEAR POWER PLANTS AND RESEARCH REACTORS

For the purposes of this publication, different types of nuclear power plants can be distinguished:

(a) Boiling water reactors;
(b) Pressurized reactors;
(c) Heavy water moderated reactors;
(d) Fast breeders which use liquid sodium as coolant.

Each one has its own particularities. These particularities will be addressed when they are relevant with respect to source and environmental measurements.

A variety of different types of research reactors exists. They range from swimming pool reactors to prototypes of nuclear power plants. Thus, monitoring programmes will depend heavily on the type of research reactor and, for those reactors in the upper end of the range (e.g. prototypes of nuclear power plants), will be similar to the programmes adopted for nuclear power plants.

Swimming pool reactors release only small amounts of radionuclides into air and water. Consequently, of the airborne discharges, only argon-41 may need to be monitored continuously on-line. Discontinuous measurements need only be performed for beta/gamma emitters and for iodine-131. When liquid discharges have to be considered, the discharge water should be analysed for beta/gamma, alpha emitters, strontium-90 and tritium before its release into the environment.

Depending on the type of research reactor, different suites of fission products may need to be considered in the event of an accidental release.

Storage of spent nuclear fuel and on-site waste storage at the facility should be considered in the design of the monitoring programme.

The remainder of this part of the appendix deals mainly with source and environmental monitoring for nuclear power plants.

Strontium-89 and strontium-90 are usually the only aerosol-bound pure beta emitters which cannot be practicably quantified by HPGe gamma spectrometry and that need to be routinely monitored in the discharges from nuclear power plants, because they might be released in significant amounts. Other radionuclides, such as iron-55 or nickel-63, might only need to be measured in special investigations to demonstrate that the assumptions made about the spectrum of radionuclides in the discharges are correct.

I.3.1. Source monitoring: Airborne discharges

Nuclear power plants are characterized by a high inventory of nuclear fuel, fission and activation products. The most important radionuclides in airborne discharges from power reactors are noble gases, isotopes of iodine, volatile compounds of tritium and carbon-14, and fission and activation products in particulate form. The use of special gas treatment systems substantially reduces the discharge of noble gases, with the result that iodine-131, even though released in small quantities, has become the most radiologically significant radionuclide present in the airborne discharges.

In the event of an accidental release, the isotopes of iodine and noble gases would still be among the most important radionuclides to be monitored.

Depending on the type of reactor, the authorized limits for airborne discharges given by the regulatory body will usually be expressed in terms of annual activities for noble gases, aerosol-bound beta/gamma emitters and isotopes of iodine. Annual discharge limits for alpha emitters, carbon-14 and tritium may also be specified.

I.3.1.1. Noble gases

The radioisotopes of the noble gases that are of interest in the discharges from a nuclear power station are listed in Table 6.

To provide data on the activities of the isotopes of the noble gases discharged into the environment and to demonstrate compliance with the authorized limits, measurements should be made continuously on-line or by drawing a sample of the discharges through the monitoring equipment.

TABLE 6. NOBLE GASES TO BE CONSIDERED IN DISCHARGES FROM A NUCLEAR POWER PLANT

Isotope	Half-life	Isotope	Half-life
^{41}Ar	109.34 min	^{131m}Xe	11.8 d
^{85}Kr	10.75 a	^{133}Xe	5.24 d
^{85m}Kr	4.48 h	^{133m}Xe	2.19 d
^{87}Kr	76.3 min	^{135}Xe	9.14 h
^{88}Kr	2.84 h	^{135m}Xe	15.29 min
^{89}Kr	3.15 min	^{137}Xe	3.82 min
		^{138}Xe	14.1 min

I.3.1.2. Particulates

The aerosol-bound beta/gamma emitters, which should be considered for measurement in the airborne discharges of nuclear power reactors, are listed in Table 7. The beta/gamma emitting radionuclides, such as cobalt-60, ruthenium-106, isotopes of iodine and caesium, are potentially important contributors in terms of possible exposures. In order to demonstrate compliance with the authorized limits, the beta/gamma emitters should be sampled on filters. The filters should be changed at appropriate intervals and analysed by HPGe gamma spectrometry shortly after the end of the sampling period.

The annual releases of alpha emitters, such as plutonium isotopes, from nuclear power plants are usually low. Nevertheless, alpha emitters should be routinely monitored. The radionuclides to be considered are listed in Table 8.

The filter from sampling the beta/gamma emitters should be analysed for strontium-90 several weeks after sampling, to allow for the decay of the short lived radionuclides.

In addition, on-line measurement of aerosols may be carried out. In this case, sampling is carried out continuously using filters and the total beta activity measured during sampling. If the accumulated activity exceeds a specified level, the filters should be changed and analysed.

TABLE 7. BETA/GAMMA EMITTERS TO BE CONSIDERED IN DISCHARGES FROM A NUCLEAR POWER PLANT

Isotope	Half-life	Isotope	Half-life
β/γ emitters			
^{51}Cr	27.7 d	^{103}Ru	39.26 d
^{54}Mn	312.3 d	^{106}Ru	373.6 d
^{57}Co	271.8 d	^{110m}Ag	249.8 d
^{58}Co	70.86 d	^{124}Sb	60.2 d
^{59}Fe	44.5 d	^{134}Cs	2.065 a
^{60}Co	5.27 a	^{137}Cs	30.07 a
^{65}Zn	244.26 d	^{140}Ba	12.75 d
^{95}Zr	64.02 d	^{140}La	1.68 d
^{95}Nb	34.97 d	^{141}Ce	32.5 d
		^{144}Ce	284.9 d
Pure β emitters			
^{89}Sr	50.53 d	^{90}Sr	28.79 a
^{55}Fe	2.73 a	^{63}Ni	100.1 a

TABLE 8. ALPHA EMITTERS TO BE CONSIDERED IN DISCHARGES FROM A NUCLEAR POWER PLANT

Isotope	Half-life	Isotope	Half-life
^{238}Pu	87.7 a	^{241}Am	432.2 a
^{239}Pu	24 110 a	^{242}Cm	162.8 d
^{240}Pu	6563 a	^{244}Cm	18.1 a

I.3.1.3. Iodine-131

Iodine-131 is the most important radioisotope of iodine with respect to dose to the public. Radioiodine may be released in three different forms: elemental, organic or attached to aerosols. These forms behave differently in the environment. In particular, the deposition velocity of elemental iodine is an order of magnitude greater than that of iodine attached to aerosols, and two orders of magnitude greater than that of organically bound iodine. Thus, it may be appropriate to distinguish between these three forms in the source monitoring programme. However, this will only need to be considered where the doses from the different forms may be significant or when the authorized limits are expressed in terms of the different forms.

On-line measurement of iodine-131 might be appropriate for nuclear power reactors, in order to provide early warning of any deviation from normal release levels.

I.3.1.4. Tritium and carbon-14

The airborne discharge of tritium is only significant with heavy water moderated reactors; it is of minor importance with boiling and pressurized water reactors.

The annual discharges of carbon-14 are fairly constant for a given type of reactor. Heavy water moderated reactors have the highest release rates — the latter are significantly higher than those from boiling or pressurized water reactors.

Consideration should be given to the monitoring of tritium and carbon-14 in airborne discharges, as appropriate. If included in the environmental monitoring programme, it should be sufficient to measure samples quarterly.

I.3.2. Source monitoring: Liquid discharges

The liquid discharges from power reactors contain fission and activation products, with the predominant radionuclides being the isotopes of caesium, cobalt, strontium, iodine and tritium.

It is normal practice to collect discharge water in storage tanks and to measure the radionuclide concentration before discharge to the environment, in order to check for compliance with the limits established by the regulatory body. During the actual discharge to the environment, the activity of the water can be measured continuously by gamma spectrometry.

In order to provide data on the quantities of gamma emitters released into the environment, a sample from each discharge water tank or a combined sample from several tanks should be measured by HPGe gamma spectrometry. The radionuclide spectrum is generally the same as that for airborne releases (see Table 7).

If continuous measurements of beta activity are not performed, the concentration of specific pure beta emitters, such as strontium-89/90, iron-55 or nickel-63, should be analysed quarterly in composite samples for environment. Phosphorus-32 should be measured monthly in liquid discharges from boiling water reactors during at least the first year of operation.

Alpha emitters, such as the isotopes of plutonium, americium and curium, should be analysed in quarterly composite samples. The total alpha activity should be measured in a first step. If the concentration exceeds a predetermined value, the sample should be analysed for specific radionuclides.

Tritium is the dominant radionuclide in liquid discharges from a nuclear power plant. It is especially important in discharges from heavy water reactors. As a minimum, tritium should be measured in weekly composite discharge water samples; however, many operators choose to measure it more frequently. In the case of a facility which releases less tritium, the tritium activity should be measured in a composite discharge water sample every month. It may not be necessary to measure carbon-14 in releases of discharge water from other facilities, if releases are insignificant or can be estimated by other means (e.g. calculated production).

Carbon-14 is discharged with water in significant amounts only from heavy water reactors. In this kind of facility, it is sufficient to measure it in monthly composite samples.

I.3.3. Environmental monitoring: Terrestrial environment

Monitoring programmes may include monthly sampling of dry deposition. Typically, measurements are made of gross beta activity. Additionally, HPGe gamma spectrometry may be undertaken.

Typical monitoring programmes also include monthly sampling of rainwater to measure wet deposition. HPGe gamma spectrometry is usually undertaken of wet and dry deposition samples. Measurements may also be made of the concentrations of tritium, potassium-40 and gross beta activity. The purpose of the measurement of potassium-40 activity concentration is so that this can be used to correct the gross beta activity concentration.

Typical soil monitoring programmes include annual sampling of the upper layer of soil at a few locations and HPGe gamma spectrometry is the primary analytical method.

Typical food and feedstuff monitoring programmes include annual (minimum frequency) to monthly (during the growing season) sampling. Monthly sampling may be desirable when significant amounts of short lived radionuclides are being discharged. Typically, measurements are made of gross beta activity concentrations. Gamma spectrometry using HPGe detectors is undertaken. This monitoring programme should include sampling of pasture grass with monthly (when animals are on pasture) sampling with, typically, measurements being made of gross beta activity and potassium-40 concentrations. Gamma spectrometry using HPGe detectors is undertaken. The concentration of carbon-14 could also be measured quarterly or annually.

Typical monitoring programmes include monthly (when animals are on pasture) sampling of milk. Usually, measurements are made of gross beta activity and potassium-40 concentrations. Gamma spectrometry using HPGe detectors is undertaken. The concentration of carbon-14 could also be measured quarterly or annually.

I.3.4. Environmental monitoring: Aquatic environment

I.3.4.1. Waters

Typical monitoring programmes for nuclear power plants include, if appropriate, regular sampling of the river water downstream or sea or lake water in the vicinity of the plant discharge point, with monthly measurements of the gross beta activity and potassium-40 concentrations and/or by HPGe gamma spectrometry, of both filtered water and the suspended sediment. The tritium concentration of the filtered water should also be measured.

Annual sampling of the groundwater from a few boreholes (the number and position will depend on the groundwater circulation scheme) close to the plant could be conducted. Measurements are made by HPGe gamma spectrometry, of both the filtered water and the suspended sediment. The tritium concentration of the filtered water should also be measured.

Typical monitoring programmes for drinking water include quarterly to annual sampling of drinking water, with measurements of the gross beta activity and potassium-40 concentrations and/or by HPGe gamma spectrometry. The tritium concentration should also be measured.

For monitoring related to heavy water reactors, tritium should be a key issue in the programme.

I.3.4.2. Bottom sediment

Typical monitoring programmes for nuclear power plants with liquid discharges to rivers, lakes or sea include annual sampling of the upper layer of the bottom sediment at one location (downstream of the plant at a place where the discharges are well mixed with the river water or in the tidal zone) or at several locations (e.g. places where people spend time on sediment for occupational or recreational purposes and close to places where water is extracted for irrigation) with measurements of the gross beta activity and/or by HPGe gamma spectrometry.

I.3.4.3. Aquatic biota

Typical monitoring programmes for nuclear power plants with liquid discharges include annual sampling of fish and plants at one location (downstream of the plant at a place where the discharges are well mixed with the river water) or several locations (at a location in the vicinity of the plant and close to commercial fishing grounds or other areas that may contribute to the exposure of the representative person) with measurements of the gross beta activity and/or by HPGe gamma spectrometry. Measurements are made by HPGe gamma spectrometry.

I.3.5. Environmental monitoring: External radiation

There are no specificities for the environmental monitoring of external radiation from nuclear power plants and the information of Section 4.4.1 is appropriate in this context.

I.4. URANIUM ENRICHMENT AND FUEL FABRICATION PLANTS

The suite of radionuclides to be found in fuel fabrication and that found in enrichment plants are comparable, thus, the source and environmental monitoring programmes for these facilities can be discussed together. The main radionuclides of interest are the isotopes of thorium, uranium and plutonium. Fission products only need to be considered if uranium or plutonium from reprocessed fuel is used.

I.4.1. Source monitoring: Airborne discharges

Depending on the kind of facility, the authorized annual discharge limits for total alpha activity are likely to vary between about 10^6 Bq and 10^9 Bq. An advantage of expressing the limits in terms of total alpha is that there is no need to discriminate between the radionuclides present, therefore, demonstration of compliance with the limits is more straightforward.

Discharge limits for beta/gamma emitters may also need to be defined if uranium or plutonium from reprocessed fuel is used. In this case, the authorized annual discharge limits for total beta/gamma plus pure beta activity might be about one or two orders of magnitude higher than those for total alpha activity.

To demonstrate compliance with the authorized limits, the total amount of airborne radionuclides discharged in a year is determined by routine measurement of the activity deposited on filters. The type of measurement of activity depends on how the authorized limits are defined, whether in terms of total activity or the activities of individual radionuclides. If radionuclide specific limits are defined, a two-step procedure might be appropriate. In the first step, the total alpha or beta activity might be measured. The second step (involving analysis of the individual radionuclides) would only be necessary if predefined levels for the sampling period are exceeded.

The sampling interval should be weekly or biweekly. If measurements of beta/gamma emitters are required, the filters should be immediately analysed. Quarterly measurements of a mixed sample might be appropriate for alpha emitters.

In addition to the routine sampling, on-line monitoring should also be considered in order to provide a warning of any unexpected release of radioactive material.

Radon-220 and radon-222 and their decay products should not need to be monitored, the immediate parents of the radon isotopes (isotopes of radium) having been removed in the processing of uranium or thorium ore. Nevertheless, their rate of production should be estimated from the fuel inventory. Furthermore, time should be allowed for the decay of any alpha emitting decay products of the

isotopes of radon that are naturally present before undertaking a gross alpha measurement.

The alpha emitters that should be considered when different types of fuel elements are being manufactured are shown in Table 9. The beta/gamma emitters and pure beta emitters that should be considered where appropriate are shown in Table 10.

I.4.2. Source monitoring: Liquid discharges

As with the other plants considered in this report, the normal practice is to collect the discharge water in storage tanks and to measure the radionuclide concentration before discharge to the environment, in order to check for compliance with the limits established by the regulatory body. When the activity levels in a batch are below the limits (or more appropriately, the limits for the batch derived from the authorized limits), the batch is discharged. In addition,

TABLE 9. ALPHA EMITTERS TO BE CONSIDERED WITH DIFFERENT TYPES OF FUEL ELEMENTS IN URANIUM ENRICHMENT AND FUEL FABRICATION PLANTS

α emitting radionuclide	Type of reactor fuel		
	Uranium	MOX	Thorium
^{228}Th			+
^{230}Th			+
^{232}Th			+
^{232}U		+	
^{234}U	+	+	+
^{235}U	+	+	+
^{236}U	+	+	+
^{238}U	+	+	+
^{238}Pu		+	
^{239}Pu		+	
^{240}Pu		+	
^{237}Np		+	
^{241}Am		+	
^{242}Cm		+	
^{244}Cm		+	

TABLE 10. BETA/GAMMA AND PURE BETA EMITTERS TO BE CONSIDERED IN URANIUM ENRICHMENT AND FUEL FABRICATION PLANTS

Isotope	Half-life	Isotope	Half-life
β/γ emitters			
^{106}Ru	373.6 d	^{125}Sb	2.76 a
^{134}Cs	2.065 a	^{137}Cs	30.07 a
^{144}Ce	284.9 d		18.1 a
Pure β emitters			
^{90}Sr	28.79 a	^{99}Tc	211 100 a
^{241}Pu	14.35 a		

continuous measurements of the discharge rate with provision of automatic termination of the discharge may be appropriate to prevent abnormal releases. The radionuclides of interest are the same as those considered for airborne discharges, except for the isotopes of radon.

I.4.3. Environmental monitoring: Terrestrial environment

Monitoring programmes may include monthly sampling of deposition. Typical monitoring programmes include annual sampling of the upper layer of soil downwind of the facility. Typical monitoring programmes may include sampling of leafy vegetables downwind of the facility. No monitoring of pasture is usually necessary. Monitoring programmes generally do not include monitoring of milk because the transfer of alpha emitting radionuclides to milk is low.

Measurements are made of the concentrations of gross beta activity, uranium and potassium-40. Additionally, HPGe gamma spectrometry should be undertaken when the facilities are using reprocessed uranium.

I.4.4. Environmental monitoring: Aquatic environment

I.4.4.1. Waters

Typical monitoring programmes for plants discharging to rivers, lakes or sea include regular sampling of the river water downstream or sea or lake water in the vicinity of the plant discharge point, with monthly measurements of the concentrations of gross beta and alpha activities, potassium-40 and uranium.

Further analysis for the individual isotopes of uranium may be undertaken as appropriate, and depending on the results of the gross alpha and beta measurements. The programmes include HPGe gamma spectrometry when the facilities are using reprocessed uranium.

Typical monitoring programmes for drinking water include annual sampling of drinking water with measurements of the concentrations of gross beta and gross alpha activities, potassium-40 and uranium.

I.4.4.2. Bottom sediment

Typical monitoring programmes for plants with liquid discharges to rivers, lakes or sea include annual sampling of the upper layer of the bottom sediment at one location (downstream of the plant at a place where the discharges are well mixed with the river water or in the tidal zone) or at several (e.g. places where people spend time on sediment for occupational or recreational purposes and close to places where water is extracted for irrigation), with measurements of the concentrations of gross beta and alpha activities, potassium-40, uranium. Further analysis for the individual isotopes of uranium may be undertaken as appropriate, and depending on the results of the gross alpha and beta measurements. The programmes include HPGe gamma spectrometry when the facilities are using reprocessed uranium.

I.4.4.3. Aquatic biota

Typical monitoring programmes for plants with liquid discharges include annual sampling of fish and aquatic plants at one location (downstream of the plant at a place where the discharges are well mixed with the river water) or at several locations (in the vicinity of the plant and close to commercial fishing grounds or other areas that may contribute to the exposure of the representative person) with measurements of the concentrations of gross beta and gross alpha activities, potassium-40 and uranium. Further analysis for the individual isotopes of uranium may be undertaken as appropriate, and depending on the results of the gross alpha and beta measurements. The programmes include HPGe gamma spectrometry when the facilities are using reprocessed uranium.

I.4.5. Environmental monitoring: External radiation

There are no specificities for the environmental monitoring of external radiation from nuclear power plants and the information of Section 4.4.1 is appropriate in this context.

I.5. REPROCESSING FACILITIES

Reprocessing plants are characterized by high radioactive inventories. The spectrum of radionuclides covers fission and activation products and actinides, and these may be present in liquid or airborne discharges. The ratios in which the radionuclides are present in the discharges may vary according to the different decontamination factors provided by the waste treatment system for the various radionuclides. In the event of a chemical or mechanical accident, these radionuclide ratios are generally maintained, although the total activities released may be significantly higher.

Unlike reactors, the short lived radionuclides (those with half-lives of less than a few weeks or so), such as the isotopes of xenon and iodine-131, will have decayed before reprocessing and therefore will not be present in routine discharges. However, in the event of a criticality accident, short lived fission products may be released.

In general, the approach to source and environmental monitoring will follow that for reactors, thus only a summary is given here.

I.5.1. Source monitoring: Airborne discharges

The only noble gas that needs to be measured routinely in the airborne discharges is krypton-85. To provide data on the released quantities, krypton-85 should be measured continuously using on-line measurement systems or by drawing a sample of the discharges through the monitoring equipment.

The aerosol-bound beta/gamma emitters that should be measured are cobalt-60 and caesium-134/137. The aerosol-bound pure beta emitter that should be measured is strontium-90 and possibly technetium-99.

Iodine-129 is the only isotope of iodine that needs to be routinely monitored in the discharges from reprocessing plants. In addition, tritium and carbon-14 should be sampled continuously and samples analysed monthly in order to estimate the annual release rates.

The alpha emitters that should be measured cover a wide spectrum: the isotopes of uranium, plutonium, neptunium, americium and curium. The beta emitting plutonium-241 should also be included.

Samples of the radionuclides collected on filters should be analysed by HPGe gamma and alpha spectrometry. In addition, analysis of strontium-90 on the filters should also be undertaken. It is recommended that when beta/gamma spectrometric measurements are performed, the same radionuclide suite be used as for source monitoring at nuclear power stations.

In addition, on-line measurements should be carried out for warning purposes. Such measurements should be undertaken for beta/gamma and alpha emitters.

I.5.2. Source monitoring: Liquid discharges

Apart from krypton-85, analysis for the same radionuclides in liquid discharges as for airborne discharges should be undertaken. Radionuclide specific measurements should be undertaken on discharge water before its discharge to the environment.

I.5.3. Environmental monitoring: Terrestrial environment

Typical monitoring programmes for the terrestrial environment include, if appropriate:

(a) Monthly sampling of deposition, downwind in the prevailing wind direction, at the point where the deposition is at a maximum and in a few other places close to where the representative persons are located.
(b) Quarterly sampling of the upper layer of soil downwind of the facility, followed by measurements using HPGe gamma spectrometry.
(c) Monthly sampling of plants in several locations in the vicinity of the plant with measurements of tritium and carbon-14 concentrations and measurement by HPGe gamma spectrometry. Samples from the same locations are also gathered annually for measurement of the concentrations of americium-241, curium-244 and alpha emitting isotopes of plutonium.
(d) An annual comprehensive sampling campaign of the local agricultural produce (various kinds of fruits and vegetables, meat and other farm products, such as eggs, cider and honey) downwind of the plant with measurements being made of the concentrations of tritium, carbon-14, strontium-90 (on specific samples), iodine-129 and actinides (on specific samples), and by HPGe gamma spectrometry.
(e) Monthly sampling of pasture in several locations in the vicinity of the plant with measurements being made of the concentrations of tritium and carbon-14, iodine-129 and by HPGe gamma spectrometry. Samples from the same locations are also gathered annually for measurements of the concentrations of americium-241, curium-244 and alpha emitting isotopes of plutonium.

(f) Monthly (when animals are on pasture) sampling of milk in several locations close to the plant. Measurements are made of the concentrations of carbon-14, tritium, iodine-129 and strontium-90, and by HPGe gamma spectrometry.

HPGe gamma spectrometry should be undertaken, and the measurements of gross beta and gross alpha activities could be sufficient in many situations for the initial screening purposes.

I.5.4. Environmental monitoring: Aquatic environment

I.5.4.1. Groundwater and surface water

Typical monitoring programmes include monthly sampling of groundwater and surface water at several locations, as appropriate, close to the facilities, with measurements being made of the concentrations of gross alpha and beta activities, potassium-40 and tritium.

I.5.4.2. Drinking water

Typical monitoring programmes include monthly sampling of drinking water at several locations around the facilities with measurements of the concentrations of gross alpha and beta activity, potassium-40, tritium and by gamma spectrometry.

I.5.4.3. Sea water

Typical monitoring programmes for reprocessing plants discharging into the sea include regular sampling of the sea water in one or a few locations close to the plant, with measurements being made of the tritium concentration and by HPGe gamma spectrometry. In addition, measurements of the concentrations of gross beta activity, potassium-40 and strontium-90, and the alpha and beta emitting isotopes of plutonium are made on monthly samples.

I.5.4.4. Bottom sediment

For fuel reprocessing plants, all of which at present are situated near the seashore, typical monitoring programmes include quarterly sampling of the upper layer of the bottom sediment at several locations in the tidal zone (downstream of the plant where people may spend time on sediment for occupational or recreational purposes) and at several locations offshore or in the tidal zone

(downstream of the outlet). Measurements are made of the concentrations of strontium-90, curium-244, americium-241, iodine-129 and technetium-99, and the alpha and beta emitting isotopes of plutonium and by HPGe gamma spectrometry.

I.5.4.5. Aquatic biota

For fuel reprocessing plants near the seashore, typical monitoring programmes include quarterly sampling of fish, molluscs and crustaceans at several locations (downstream of the plant outlet; in fishing areas around the plant; in aquaculture farms downstream of the plant). They also include quarterly sampling of molluscs and seaweed in several locations (onshore downstream of the plant outlet; in mollusc fishing areas around the plant; in fish farms downstream of the plant). Measurements are made of the concentrations of carbon-14, technetium-99, of the alpha and beta emitting isotopes of plutonium and by HPGe gamma spectrometry.

I.5.5. Environmental monitoring: External exposure

Typical monitoring programmes include the measurement of the integrated external radiation level at 10 or more stations at appropriate intervals around the site boundary. In addition, programmes include the recording of ambient gamma dose rates at several locations around and close (e.g. 1 km) to the facility. One of these stations should be downwind of the prevailing wind direction and close to the nearest villages or cities. All stations should be equipped with on-line transmission of data.

I.6. NORM FACILITIES

Radionuclides of natural origin are ubiquitous in the environment. Where the concentrations of uranium or thorium are high enough, then mining may be feasible. However, the widespread nature of radionuclides of natural origin means that other materials extracted from the ground are likely to contain these radionuclides. In some cases, the concentrations of these are sufficient to be of concern from a radiological protection point of view. The residues from the extraction of materials may also be significant. In some cases, the extraction and processing of the material may have concentrated the radionuclides in these residues. Naturally occurring radioactive material (NORM) is the term used to qualify these materials. It is defined as radioactive material containing no significant amounts of radionuclides other than naturally occurring

radionuclides [1]. The exact definition of 'significant amounts' would be a regulatory decision. However, Safety Standards Series No. RS-G-1.7 [197] provides guidance on this. In particular, it is stated that it is usually unnecessary to regulate radioactive material in activity concentration below the following values: 1 Bq/g in the case of uranium-238, uranium-235 and thorium-232 (with the value being applied to the parent of the decay chains) and 10 Bq/g in the case of potassium-40. Uranium and thorium ores would fall within the definition of NORM. The mining of these ores and the management of the wastes arising are normally subject to regulatory control.

Many of the industries and processes involving NORM handle large quantities and produce large quantities of residue. As with any industry handling radioactive materials, a graded approach commensurate with the magnitude of the hazard should be applied to the regulation of NORM industries. This also applies to the monitoring programmes that should be adopted.

NORM residues may give rise to exposure of members of the public via the following pathways:

(a) External exposure to gamma radiation emitted by the material;
(b) Intakes of material due to dust inhalation, either directly or via resuspension;
(c) Intakes of material by ingestion, either directly (e.g. inadvertent ingestion of contaminated soil) or via the food chain;
(d) Inhalation of radon (and very rarely, thoron) decay products produced in the air from released radon (or thoron) from the material.

All of these exposure pathways are part of the means by which all people are exposed to radiation of natural origin, so it is necessary to be able to distinguish the additional exposure arising from activities involving NORM.

The radionuclides present in NORM residues are those of the uranium (and thorium) decay series, and the approach to monitoring should be similar to that used with uranium and thorium mines, appropriately graded according to the situation. A significant difference, however, is that the uranium and thorium may not have been removed or may be concentrated in some products. Thus the focus of any source monitoring programme should be directed towards characterizing the various components and streams of radioactive releases primarily from the point of view of activity concentrations of the radionuclides of the uranium and thorium decay chains: primarily, the parents themselves and the isotopes of radium and, in some cases, polonium-210 and lead-210. The focus of the environmental monitoring programme should be directed towards the measurement of these elements and radionuclides in relevant environmental media. The relevant environmental media will depend on the actual residue

management practice, whether there are significant discharges to air or water, and on the treatment of the solid residues. Where there are significant uncovered stockpiles of residues, consideration will need to be given to monitoring radon and its decay products in air, airborne dusts and external radiation levels [15], which applies to monitoring programmes related to the residues of uranium mining and milling facilities would be appropriate.

I.7. RADIOPHARMACEUTICAL FACILITIES AND HOSPITALS

Radiopharmaceutical facilities and hospitals may potentially use a variety of radionuclides with very specific chemical forms (Table 11). The monitoring programme implemented for a particular radiopharmaceutical facility or hospital is, therefore, dependent on the inventory of involved radioactive materials (radionuclides, chemical forms, specific and absolute activity), the nature of the operations conducted and technical specification of the discharge treatment facilities. It should be noted that a larger number of radionuclides are used in research and development of new treatments, and research and facilities involved in such activities may feasibly employ a wider range of radioactive materials and conduct operations involving processes not encountered in other hospitals.

While most medical radionuclides are of short half-life, the half-life of their progenies may be considerably longer (e.g. technetium-99m yielding long lived technetium-99) and the monitoring design should, therefore, consider progenies.

I.7.1. Source monitoring: Airborne discharges

Depending on the radioactive materials in use at the facility, it may be necessary to conduct monitoring for airborne gross alpha/beta discharged from stacks. This monitoring may be both for aerosols and gases such as iodine vapour, using gross alpha/beta counters.

TABLE 11. RADIONUCLIDES COMMONLY ENCOUNTERED IN MEDICINE

Isotope	Half-life	Isotope	Half-life
^{99}Mo	65.94 h	^{90}Y	64.0 h
^{99m}Tc	6.01 h	^{131}I	8.02 d
^{89}Sr	50.53 d	^{133}Xe	5.24 d
^{186}Re	3.72 d	^{32}P	14.26 d

I.7.2. Source monitoring: Liquid discharges

Liquid discharges from facilities should be monitored for the radioactive materials in use at the facility. This is typically conducted by measurement of a homogenized sample drawn from the discharge tank prior to batch discharge. Due to the potential for exposure of sewage treatment plant operators, in some cases, sampling of liquors from sewage treatment plants to which the facility discharges may be required, the frequency and timing of which depends upon the discharge pattern of the facility. Measurement methods will vary depending on the radioactive materials in use but should, as appropriate, include gross beta or gamma spectrometric measurements.

I.7.3. Source monitoring: Direct radiation

For licensed facilities, periodic monitoring of the direct radiation in the immediate environment of the facility could be considered (e.g. once per year).

I.7.4. Environmental monitoring: Terrestrial environment

Monitoring the terrestrial environment is not typically necessary, however, where a facility discharges to a sewage or other treatment plant where the sludge generated may be subsequently used as land amendments or fertilizer, annual sampling of soil from land to which the sludge is applied may be conducted. Such environmental monitoring is usually conducted by designated agencies or bodies. Analyses are typically made by gross beta or gamma spectrometry.

I.7.5. Environmental monitoring: Aquatic environment

Radiopharmaceutical facilities and hospitals do not typically discharge directly to freshwater bodies or the sea, but in cases where a hospital discharges to a sewage treatment plant, annual sampling of sediments from the water course receiving treated waters from the plant may be required. As for the terrestrial environment, such monitoring is usually conducted by designated agencies or bodies. Samples may be measured for gross beta and by gamma spectrometry, paying attention to the potential presence of long lived progenies.

I.7.6. Environmental monitoring: External exposure

Monitoring of the external exposure outside a radiopharmaceutical facility is not typically conducted.

Appendix II

SPECIAL FEATURES OF STACK MONITORING AT NUCLEAR FACILITIES

II.1. AIRBORNE DISCHARGES

The approach to monitoring airborne discharges is shown diagrammatically in Fig. 14.

II.1.1. Noble gases

For measurement of the radioisotopes of noble gases, gross beta activity measurement and/or radionuclide specific activity measurement are recommended, as appropriate. To avoid errors due to contamination by particulate material, the air in the sampling stream should be filtered before measurement. In on-line monitoring, the counting time depends on the required detection limits for noble gases and usually should not be longer than 1 h. For demonstration of compliance with the authorized values, the results of the

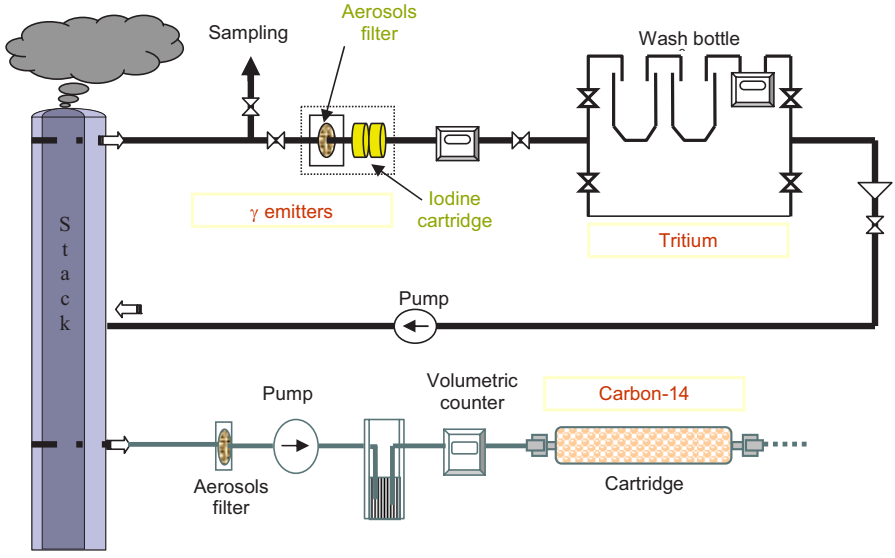

FIG. 14. Airborne discharge monitoring arrangement at a nuclear power plant.

measurements accrued over the entire year should be used to calculate the annual discharge.

In the case of off-line monitoring, if the activity concentration of the noble gases is sufficiently high, measurement of the filtered sample in a container of appropriate volume, at atmospheric pressure, may be sufficient. Where this is not the case, a larger volume of the sample should be collected and compressed to a high pressure in a suitable container to achieve an appropriate MDA.

Noble gases can also be sampled using a cold trap, for example, activated charcoal at low temperature. This permits the accumulation of the noble gases in a small volume.

II.1.2. Aerosols

Beta/gamma emitters

Aerosol-bound beta/gamma emitters are sampled continuously in a partial air stream on an aerosol filter. The filters should be changed at least every week and analysed using an HPGe gamma spectrometer not later than two days after their removal. The activity of short lived radionuclides should be corrected for radioactive decay.

For on-line measurements, the aerosol-bound beta/gamma emitters are measured continuously on the filters for gross beta activity and/or using gamma spectrometry. The measurement system should be such that warning levels can be detected, these being defined as an appropriate fraction of the authorized discharge limit being released within a certain time period. When on-line measurements indicate a level in excess of the warning levels, the filters should be changed and measured immediately.

Pure beta emitters

Aerosol-bound pure beta emitters are measured using the same filter as for beta/gamma emitters, the analysis of the pure beta emitters being carried out after the measurements by gamma spectrometry. Strontium-90 is usually the only aerosol-bound pure beta emitter that needs to be routinely monitored in the discharges from nuclear facilities, which could release significant amounts. The caesium-137 concentration is often used to trigger strontium-90 analysis. Other radionuclides, such as iron-55 or nickel-63, might only be measured in special investigations to demonstrate that the assumptions made about the radionuclide spectrum are correct.

Quarterly analysis of pure beta emitters might be sufficient to demonstrate compliance with authorized limits for nuclear power plants. A higher frequency is recommended for reprocessing plants, with the weekly filters for the appropriate period being combined for radiochemical analysis.

Alpha emitters

Aerosol-bound alpha emitters are sampled discontinuously in a partial air stream on the same filter type as used for beta/gamma emitters. Only in facilities with low discharges of alpha emitters might it be appropriate to use the same filters as used for the measurement of beta/gamma emitters. In these cases, the analysis of the alpha emitters would be undertaken after the measurements by gamma spectrometry. Otherwise, separate sampling should be undertaken.

The sampling period should not be longer than two weeks because of the possibility of overloading the filter. The frequency of measurement depends on the type of facility. For nuclear power plants and research reactors, a quarterly analysis is sufficient in order to calculate the annual discharge. For reprocessing plants, enrichment plants and fuel fabrication plants, the measurement frequency should be one month or less. A two-step measurement procedure might be appropriate. In a first step, the total alpha activity would be measured after allowing for decay of the decay products of radon-222 and radon-220. This step might be sufficient for all facilities except reprocessing plants. The second step would involve radionuclide specific analysis of the filters or parts of the filters only if a defined level for the gross alpha activity is exceeded. This level might be defined in terms of mean air concentration (Bq/m^3) or discharge rate (Bq/week or month).

On-line measurements of alpha emitters only are necessary for reprocessing plants and MOX fuel fabrication plants. Sampling using an aerosol filter in a partial air stream would be undertaken continuously and the gross alpha activity accumulated would be measured automatically. The filters should be changed with a frequency of about every 12 hours. However, if predefined levels are exceeded, the filters should be changed immediately and analysed by alpha spectrometry.

II.1.3. Tritium, carbon-14, radioiodine, volatile radionuclides

II.1.3.1. Tritium

Tritium may be discharged in the forms of water (HTO) or gas (HT). In addition, organically bound tritium might be present in small amounts. However,

for the purpose of assessing the environmental impact of tritium, it is usually sufficient to assume that the tritium is in the form of HTO.

Several methods may be used to determine the total tritium in the filtered air stream sample. Tritium gas must first be oxidized by passing the air stream over heated copper oxide wool. The following methods are currently used to trap the tritiated water:

(a) A cold trap to condense the tritiated water;
(b) A drying agent such as silica gel;
(c) A bubble system containing water.

The trapped tritiated water should be measured in a scintillation counter about 4–12 times a year.

II.1.3.2. Carbon-14

Carbon-14 may be discharged in the form of oxides of carbon (i.e. as CO or CO_2), hydrocarbons and, in small quantities, in other organic forms. However, for the purpose of assessing the environmental impact of carbon-14, it is usually sufficient to assume that it is in the form of $^{14}CO_2$.

Samples may be taken using bottles or pressurized containers. Aluminized plastic bags may also be used. These permit collection of larger samples and, hence, enable a lower detection limit to be obtained. However, continuous sampling over a week or a month may be preferable, as the short term discharge rate of carbon-14 compounds may vary widely, depending on the operating conditions.

Several methods may be used to measure carbon-14 activity in airborne discharges. One method is the direct measurement of carbon-14 in a sample of the discharge in a gas counter. Another method is to oxidize the carbon-14 compounds completely to carbon dioxide using a catalytic oven and then precipitating the carbon-14 as barium carbonate. The carbon-14 is then solubilized using a sodium hydroxide solution and measured in a liquid scintillation counter. However, since most of the carbon-14 is likely to be in the form of the dioxide already, it may be sufficient simply to absorb it in a sodium hydroxide solution, followed by liquid scintillation counting. Continuous sampling over weeks or months is recommended. Carbon-14 should be measured in a liquid scintillation counter about 4–12 times a year.

II.1.3.3. Radioiodine

The aerosol-bound isotopes of iodine may be analysed with other beta/gamma emitters. Elemental and organically bound isotopes of iodine, however, need to be sampled, after filtration to remove particulates, using special filters that absorb iodine. The sampling period for discontinuous measurements should not be longer than one week and the samples measured within 24 hours. The measured activity should be corrected for radioactive decay.

Elemental and organically bound isotopes of iodine are also the chemical forms that should be monitored when on-line measurements are required. As with discontinuous sampling, the air stream is first filtered to remove particulates and the isotopes of iodine are absorbed on an iodine filter. The radioiodine activity is measured continuously as it accumulates on the filter. Warning levels should be defined in such a way that a release of about 1×10^6 Bq/h can be detected.

Appendix III

REVIEW OF MEASURING EQUIPMENT AND TECHNIQUES

III.1. EXTERNAL RADIATION MEASUREMENTS

The instruments used for dose rate measurements for source and environmental monitoring are similar. Thus, most instruments used for measuring radiation fields in and around a facility (such as area monitors and survey meters) may be appropriate for environmental use, provided that they are sensitive enough for this purpose and, where necessary, are made weatherproof. The following considerations apply to instruments intended for environmental use.

Radiation fields in the environment are usually rather uniform because the sources are extended or the distances from the source are large and the radiation scattered. However, this does not mean that the requirement of uniformity of directional response of environmental monitoring instruments is less stringent. Attention should be paid, therefore, to the source–detector configuration in the calibration of environmental monitoring instruments with a non-uniform directional response.

Environmental radiation monitors are often installed in remote areas where the stability of the power supply might be unsatisfactory. In such cases, the monitors should be equipped with voltage stabilizers as well as an emergency power supply, which is usually a rechargeable battery of adequate capacity. Solar powered and battery powered instruments are commercially available for environmental measurements in remote areas.

Monitoring data can be transmitted by telemetry, when necessary or desirable. Data can also be downloaded to a portable computer periodically at the monitoring sites.

III.1.1. Gamma radiation

Some typical instruments for direct radiation measurements are listed in Table 12.

III.1.1.1. Installed monitors

High pressure ion chambers filled with argon are well suited for the measurement of absorbed dose rate in air at background levels (of the order of 10 nGy/h) up to several 10 mGy/h. Such instruments are available for field use in routine monitoring programmes.

TABLE 12. INSTRUMENTATION FOR DIRECT RADIATION MEASUREMENTS

Instrument or method	Typical application	Minimum detectable dose rate	Comments
GM survey meter	Locating contamination, dose rate estimates	100 nGy/h	Durable, reliable instrument; energy dependent
Scintillation survey meter	Locating contamination, dose rate estimates	10 nGy/h	Good sensitivity; energy dependent
Scintillation dose monitor	Accurate dose rate measurements	10 nGy/h	Line power may be needed, portable but not a survey instrument
Pressurized ion chamber	Accurate dose rate measurements	10 nGy/h	Accuracy ±20% at 100 nGy/h, line power may be needed, not a survey instrument
TLD	Dose measurements, indoor and outdoor	10 μGy	
In situ gamma spectrometer	Accurate dose rate measurement, also nuclide specific	10 nGy/h	Large electronic package, line power required battery model available
Glass dosimeter	Dose measurements	10 μGy	

Scintillation detectors such as thallium doped sodium iodide (NaI(Tl)) are popular for the direct measurement of ambient radiation fields because of their high sensitivity. Since the energy response of such detectors differs from that of air or tissue, some means of correction must be applied for dosimetric purposes. For energy compensation, the detector is covered with an appropriate filter to reduce the response to low energy gamma rays. Alternatively, such detectors can be used in gamma spectrometry and the detector response calibrated as a function of energy. A drawback, however, is that the detectors are temperature dependent, although spectrum stabilization can be used to overcome this, and they exhibit poor resolution.

Scintillation type monitors, if used with multichannel analysers, can provide the advantage of measuring the photon energy spectrum, which is particularly useful for the investigation of abnormal readings, since it may be possible to identify individual radionuclides. Analysis of environmental gamma rays by gamma spectrometry using scintillation or HPGe detectors is often employed in special monitoring programmes and can be used to calculate dose to

air or other media. The performance of these instruments is compared in Table 12, which also includes survey instruments and TLDs.

III.1.1.2. Survey instruments

Conventional survey meters equipped with 25 mm diameter × 25 mm NaI(Tl) scintillators or Geiger–Müller (GM) probes have adequate sensitivity to measure background dose rates. However, they have a very poor energy response for dosimetric use, although the response can be improved with suitably designed filters. The energy threshold should be noted when such survey meters are used for the measurement of X rays or gamma rays from radionuclides, such as iodine-125, xenon-133 and americium-241. Portable battery operated survey meters for environmental use are available; they are equipped with larger sized NaI(Tl) scintillation detectors or GM tubes covered with a filter for energy compensation. The latter reduces or eliminates the energy response problem.

III.1.1.3. Integrating dosimeters

Most personal dosimeters, such as film badges, TLDs, fluorescent glass dosimeters and pocket dosimeters, may be used for measuring integrated dose in environmental monitoring. Of these, TLDs are preferable because of their stability and high sensitivity. In a typical case, they are left in the environment for 3–6 months. Due to the long exposure time in the environment, the 'fading' (i.e. loss of signal) should be low, preferably less than 10%. For environmental monitoring, calcium sulphate dosimeters, as well as other types, are suitable for determining the integrated dose at a normal level (0.1–0.5 mGy) with sufficient accuracy. The TLD reader should be calibrated every 3–6 months with TLDs from the same batch as used in the environmental monitoring programme, by irradiation in a standard gamma ray field. A comparison of the performance of various types of TLDs is given in Table 13.

III.1.1.4. Electron fields (beta radiation)

Thin walled cylindrical and so-called pancake type GM tubes have been developed for measuring electron fields in the environment. A pair of such counters (one bare, the other covered with filters thick enough to stop electrons) is installed in the environment and the difference in readings of both counters is interpreted as the contribution from electrons. The electron fluence rate will thus be known but it cannot be converted into absorbed dose rate or equivalent dose rate because no energy information is available from such instruments. By using

TABLE 13. COMPARISON OF TLDs FOR ENVIRONMENTAL RADIATION MEASUREMENTS

TLD phosphor	Form	Package and shielding	Dose range	Min. photon energies[a] (keV)	Energy dependence to 1 MeV (%)	Comments
LiF	Extrusion	None	50 μGy to 10^3 Gy	15	±25	Requires careful annealing; relatively energy independent; neutron sensitive in natural form; depleted form available
Copper doped LiF						About 25 times more sensitive than TLD-100
CaF_2:Mn	Powder on wire, extrusion	Glass capsule, metal case and shield	10 μGy to 10^2 Gy	25	±25	Less stringent annealing requirements; capsule may cause self-dosing; some energy dependence; some room temperature fading
CaF_2:Dy	Extrusion	Tantalum and lead shield	5 μGy to 10^2 Gy	50	±20	Low triboluminescence: high initial fading; careful shielding and annealing required
$CaSO_4$:Tm $CaSO_4$:Dy $CaSO_4$:Mn Mg_2SiO_4:Dy	Powder	Capsule and metal shield	<1 μGy to 0.2 Gy	30	±40	High sensitivity; low fading; high energy dependence relative to air or tissue; metal shield available for energy dependence compensation

TABLE 13. COMPARISON OF TLDs FOR ENVIRONMENTAL RADIATION MEASUREMENTS (cont.)

TLD phosphor	Form	Package and shielding	Dose range	Min. photon energies[a] (keV)	Energy dependence to 1 MeV (%)	Comments
BeO	Powder or disc	Capsule to 2 mGy	20 μGy	15	±25 type	Some fading; high triboluminescence for disc

[a] For packaging indicated; may be altered by additional shielding.

plastic scintillation detectors in place of the GM counters, dose measurement would be possible.

III.1.1.5. Neutron fields

Among various kinds of neutron detectors, barium fluoride (BF_3) based counters with a combined moderator–absorber are the most practical instruments for measuring environmental neutron fields because of their sensitivity and high neutron–gamma discrimination characteristics. The detector, which is commercially available, has to be connected to a pulse counter for measuring neutron dose rates at background levels because the counting rate will be too low to be measured by a count rate meter in such low level neutron fields. Nevertheless, this meter has the advantage of giving readings directly in operational quantities.

For the measurement of neutron fluence, any type of personal neutron dosimeters may, in principle, be applied in environmental monitoring. Solid state nuclear track detectors (SSNTDs), such as CR-39™[18] (allyl diglycol carbonate), can be used without any need to consider fading for exposure periods greater than one month in the environment.

Subtraction of the gamma ray contribution is important for thermal neutron measurements. Photographic films partly covered with tin and cadmium filters yield significant results for a thermal neutron dose of 0.1 mSv in a gamma background of about 1 mSv. When TLDs are used for thermal neutron measurements, a pair of ^{6}LiF and ^{7}LiF or a pair of $^{6}Li_2{}^{10}B_4O_7$ and $^{7}Li_2{}^{11}B_4O_7$

[18] CR-39 is a trademark product of PPG Industries.

chips can be used. Their sensitivity and gamma discrimination is similar to that of the film badges mentioned.

III.2. MONITORING AIRBORNE DISCHARGES

III.2.1. Radioactive noble gases

Simple flow type detection chambers are used for the integrated measurement of noble gas releases. Compression of the sample gas into the chamber and use of an adsorbent material, such as cooled active charcoal, are effective in increasing the detection efficiency, but are not easy to apply for routine monitoring. The detection chamber may work as an ion chamber, or may be equipped with a scintillation detector. When the dominant component of the discharge is krypton-85, plastic scintillators should be used; otherwise NaI(T1) scintillators can be employed. Ion chambers having volumes ranging from 1 to 10 L are usually used; they have a response, which decreases with increasing beta particle energy. A detection chamber of 50 cm × 30 cm × 6 cm equipped with a plastic scintillator of about 15 cm in diameter and 0.5 mm thickness has an almost flat response with beta particle energy within the range of about 100 keV–2 MeV.

Radionuclide specific analysis of the noble gases is required to provide quantitative data on the radionuclides discharged into the environment. HPGe detectors are sometimes used for continuous gamma spectrometry. When discharge flow rates are low, it might be appropriate to use a sample compression technique to determine the composition of the released noble gases. This method necessitates the collection of compressed air samples in pressure bombs followed immediately by analysis by gamma spectrometry.

III.2.2. Aerosols

III.2.2.1. Beta and gamma activity

For on-line monitoring, moving filter tape in combination with one or more radiation detectors should be used to measure gross beta/gamma activity. An end-window GM counter, a gas flow counter or a plastic scintillation detector can be used for beta/gamma measurements. Radon-222 and radon-220 decay products will also deposit on the filter and these should be allowed to decay before measurement. A delay of 4 h after termination of sampling is sufficient to allow for the decay of radon decay products; a delay of 3 d is necessary with thoron decay products. Alternatively, a radionuclide spectrometric technique could be used.

The pumps used for active sampling should be calibrated and they should also be reliable, in order to obtain consistent results. Alternatively, a mass flow controller could be used to maintain steady flow rates.

Radionuclide specific analysis of the weekly filter samples should be performed with an HPGe detector.

III.2.2.2. Alpha activity

For alpha emitting radionuclides, alpha spectrometry can be used to analyse the sample on a filter. To obtain high counting efficiency and good energy resolution, a filter of good surface retention, such as a membrane filter, and a relatively short sampling time should be used to avoid too much buildup of material and the consequential self-shielding. Silicon semiconductor detectors and gridded ion chambers can be used for alpha spectrometry. An advantage of gridded ion chambers is that they have larger sensitive areas and can accommodate larger filter sizes.

To undertake radionuclide specific analyses, it is usually necessary to ash combined filters collected over a three-month period. The ash can be analysed by alpha spectrometry or by further radiochemical treatment for the separation of specific radionuclides. The separated radionuclide is usually electroplated onto a small metal disc or co-precipitated, and filtered on a membrane filter and measured with a silicon semiconductor alpha spectrometer.

III.2.2.3. Pure beta emitters

For the measurement of pure beta emitting radionuclides, it is useful to combine the filters that have been collected over a three-month period in order to improve the sensitivity of the measurement. An appropriate radiochemical procedure should be established for the separation of each pure beta emitting radionuclide. The separated pure beta emitting radionuclides can be measured in a beta counter.

III.2.3. Radioactive iodine

A conventional cartridge containing potassium iodide or triethylene diamine (TEDA) impregnated activated charcoal is generally a suitable collection device for low level iodine monitoring, because it maintains a high collection efficiency over long sampling periods. Continuous monitoring can be achieved by placing a radiation detector near the cartridge, although it should be recognized that there may be background interference due to the presence of other radionuclides. Consequently, if better sensitivity and accuracy are required,

the cartridge should be removed from the holder and analysed by HPGe gamma spectrometry. To avoid interference by noble gases absorbed in the charcoal, silver nitrate impregnated zeolite or alumina is used instead. However, the collection efficiencies are slightly lower.

Differential monitoring of the various chemical species of airborne iodine is possible by using, for example, a membrane filter, charcoal impregnated filter papers or potassium iodide impregnated charcoal cartridges.

III.2.4. Tritium

Flow type ion chambers are used for the continuous monitoring of airborne tritium if interference by other airborne radionuclides is not anticipated and no differentiation of the chemical forms of tritium, especially between HT and HTO, is necessary.

To quantify the discharge of tritium in the form of HTO, water vapour in the air is either condensed by cooling or collected on silica gel or a molecular sieve, and measured by liquid scintillation counting. Measurements of temperature and relative humidity of the air during the period of sampling make determination of the collection efficiency unnecessary. When the total tritium concentration in air is required, any tritium not in the form of HTO must first be converted into tritiated water by catalytic oxidation and collected as described previously.

III.3. MONITORING LIQUID DISCHARGES

III.3.1. Gamma emitters

Radionuclide specific analysis of the gamma emitters in liquid discharge samples can be undertaken directly using an HPGe detector. The counting efficiency can be increased by the use of Marinelli re-entrant beakers. This method is usually sufficient for decision making on the discharge of liquid discharges into the environment, as well as for calculation of the total activity discharged in a year.

III.3.2. Alpha and pure beta emitters

For the determination of the gross alpha and beta activity concentrations, samples can be evaporated to dryness and then measured with an alpha or beta counter. Many laboratories use thin window (80 $\mu g/cm^2$) gas flow proportional counters to measure the alpha and beta count rates simultaneously.

If radionuclide specific measurements are required, appropriate radiochemical techniques have to be used to separate the individual radionuclides. Only thin samples, which can be obtained by electroplating or co-precipitation and filtering on membrane filters, are suitable for alpha counting. Alpha particle emitting radionuclides can be measured with silver activated zinc sulphide (ZnS(Ag)) scintillation detectors (gross counting) or silicon semiconductor detectors (spectrometry). Beta counting can be done with GM or proportional counters of various types, depending on the activity level to be measured. Liquid scintillation counters are also used for specific radionuclides separated from discharge samples by solvent extraction techniques.

III.3.3. Tritium

Tritium in the form of tritiated water can be separated from other radionuclides by distillation and measured with a liquid scintillation counter.

III.4. SAMPLING AND MEASUREMENT EQUIPMENT FOR ENVIRONMENTAL MONITORING

The following sections provide some general information and further sources of more detailed information as to sampling and measurement techniques for the environmental monitoring of radionuclides.

III.4.1. Sampling of environmental materials

Sampling of environmental materials is primarily concerned with obtaining representative samples of the material concerned in a manner that will not impinge upon the accuracy or precision of the final analytical result. For various materials, precautions are required to ensure that these two conditions are met.

III.4.1.1. Sampling of air

Sampling of ambient air as part of an environmental monitoring programme is conducted using large volume air samplers. Such devices consist of a sample collector, a sample collector holder, an air mover and a flow measurement device. Sample collectors depend on the nature of the analyte and are primarily filter papers for aerosols and particulates. The filter papers can be of a range of sizes but typically tend towards large sizes (radii of the order of tens of centimetres) for environmental purposes.

Selection of the material of the filter paper should be based upon the subsequent measurement to be applied. Cellulose filter papers are amenable to subsequent dissolution for radiochemical analysis, whereas glass fibre filter papers may not. Membrane filter papers are appropriate where gross alpha/beta measurements may be made as particles are held towards the surface of the paper and do not penetrate into the fibres resulting in self-shielding of alpha or beta particles. Such filters tend to be smaller in size and are exposed to smaller air volumes to avoid clogging. After the sample is taken, filter papers should be handled with care to avoid loss of sampled material and are typically folded to ensure the sampled material is held within the paper itself. Filter papers may be folded and compressed into suitable geometries for direct counting by gamma spectrometry, may be presented unmodified for alpha/beta counting or may be processed further (after direct counting) for radiochemical analysis.

Other collectors for air monitoring include activated charcoal canisters over which the air sample is passed and which serve to collect iodine species, impregnated filter papers for the collection of specific species, cold traps for the collection of gases, or bubblers through which air is passed and which serve to trap specific species such as tritium or radioactive CO_2. The majority of these collectors are mounted in series, as the collection efficiency of such collectors is usually significantly less than 100%. Some of these collectors may be counted directly by gamma spectrometry or may be further processed for alpha/beta counting or radiochemical analysis. For radioactive gases, the gas may be liberated from the collector by a variety of means prior to analysis.

A sample holder is that component of the air sampler which serves to support the sample collector and expose it to the passing air sample. The holder should not damage the collector nor should it serve to ‘channel’ the sample over specific parts of the collector. The holder should be such that no sample is directed away from the collector.

The air mover is that component of the air sampler which passes the sample over the collector. The mover should not be sensitive to pressure differentials and should be able to maintain a constant movement of air over the collector irrespective of the buildup of particles on the collector and subsequent clogging. The air mover should not in any way impede or affect the passage of sample over the collector.

A flow meter is a necessary component of the air sampler and serves to determine the total amount of air that has passed over the collector. Such devices should be calibrated and regularly checked to ensure correct operation within specifications.

Air samplers should be positioned in order for the intake to be approximately at the height of 1.5 m, such that the air sampled is that which would be inhaled by the representative person. The inlet should not be vulnerable

to intake of soil particles or other materials, and the outlet should be positioned such that the air that has passed the collector cannot enter the inlet. The entire sampler should be placed away from buildings or structures (which can affect the representativity of the sample) and away from roads, factory vents or other features which may affect the quality of the sample obtained. Further relevant information is to be found in Refs [53, 95, 99, 197, 198].

III.4.1.2. Sampling of deposition

Wet deposition is sampled using collection devices of known cross-sectional areas for the collection of rain and/or snow. Typically constructed of polyethylene or stainless steel, the devices feed into plastic drums or other collection devices. After a given period, the sample collected is analysed by gamma spectrometry or other methods. The sampling procedure should ensure that cross-contamination is avoided between samples, and the device itself must be positioned such that overhanging structures or trees do not affect the sample. The collector must be perfectly horizontal to ensure unbiased sampling and should be positioned high enough such that resuspended particles due to rain impact on soil cannot enter the collector.

Dry deposition devices are often mounted in tandem with wet deposition devices and typically feature a rain sensor such that the device is covered during rainfall. Collected material can be rinsed into the collection device using distilled water for subsequent analysis. The siting of the collector should be subject to the same considerations as applied for wet deposition collectors.

III.4.1.3. Sampling of soils

Sampling of soils may be conducted in a number of different ways. Common to all methods of sampling of soils is that the materials from which the samplers are constructed should not affect the sample with respect to either contamination of the discrete sample or cross-contamination between subsequent samples. Samples should be taken from the upper layers of soil (within 2 cm) for the measurement of deposited activity, and sample information should include the wet density of the sample, approximate volume taken, approximate cross-sectional area of the sample, etc. Taking surface vegetation with the soil sample should be avoided as far as is practicable. Large stones and other materials should be removed.

Sampling of soils at depth (cores) should be conducted using appropriate devices, with particular attention being paid to avoidance of the introduction of surface materials to deeper layers of the core, or excessive compression or elongation of the core. The core may be conveniently sliced into sections after

freezing. The peripheral material from the circumference of each slice can also be removed prior to analysis, to avoid contamination from surface layers.

Information about soil sampling for the purposes of radioactivity monitoring can be found in Refs [104, 106].

III.4.1.4. Sampling of sediments

Sampling of sediments may consist of either sampling of surface layers or sampling of deep sediment layers. Sampling of surface sediments is conducted in a manner similar to that for soils, with the surface layer being taken using an appropriate tool and avoiding cross-contamination. Sampling of deeper sediments may be achieved using appropriate coring devices for near shore/intertidal sediments or using a variety of box or impact coring devices for deeper water sediments.

For all sediment sampling, particular attention must be paid to the fact that radionuclides are often associated primarily with small particle sizes which tend to be lost easily, particularly during the ascent of a sample from deep waters. Attention should be paid to the retention of small particles during sediment sampling. This can be facilitated by taking a large monolith of sediment and extracting a smaller core from the centre where loss of material during sampling is likely to have been least. Coring of sediment monoliths in this manner should be conducted using the same precautions as for soil coring.

The matter of sediment sampling has been fully elaborated upon in IAEA-TECDOC-1360, Collection and Preparation of Bottom Sediment Samples for Analysis of Radionuclides and Trace Elements [199], and further information can be obtained in Refs [135, 200–202].

III.4.1.5. Sampling of plants

Sampling of plants should be conducted such that the sample taken is representative and appropriate measures should be employed to ensure this. Precautions should be taken to ensure that adhering soil is not included in the sample.

III.4.2. Sample preservation

An important difference between sampling for source monitoring and for environmental monitoring is the time lapse between sampling and measurement. For source monitoring, the majority of samples may be measured with a relatively short lapse between sampling and actual analysis. For environmental programmes, time periods of weeks or months may exist between the sample

being taken and the actual analysis, although good laboratory practice should serve to keep this period to a practicable minimum. Due to this time lapse and the complexity of environmental samples in relation to both physical and chemical properties, careful consideration should be paid to how the sample is preserved such that processes which may occur during the storage period do not adversely affect the analytical result with respect to either accuracy or precision.

III.4.2.1. Liquids

A number of processes can affect the behaviour of radionuclides within liquids. Adsorption of radionuclides to the walls of a sampling container may occur, as may biological processes which can alter parameters of liquids such as pH or the oxidation state of radionuclides in the sample, perhaps impacting the solubility of the analyte radionuclide. Such effects may be mitigated through the addition of acids, oxidizing/reducing agents or stable carriers. Such methods should be applied only after careful consideration of the problem. The effects of such measures should be fully evaluated with respect to subsequent analytical procedures that will be applied. Liquids such as milk may require the addition of preservatives to prevent coagulation.

III.4.2.2. Soils

Soils may undergo a variety of processes that can have an impact on the speciation of radionuclides although, in general, freezing or drying serve as an effective preservation measure but should only be conducted after consideration of the radionuclide involved.

III.4.2.3. Vegetation

Vegetation and other biological materials are best frozen as rapidly as possible prior to analysis.

III.4.3. Measurement equipment

Equipment for the measurement of radioactivity as part of an environmental monitoring programme is typically laboratory based, although there are some exceptions. The instrumentation for measurement of environmental samples can be conveniently grouped according to the nature of the radiation that the radionuclide being analysed emits. Although full descriptions of instrumentation are beyond the scope of this report, some considerations for the use of such

instruments in relation to the measurement of environmental samples is presented in the following sections.

III.4.3.1. Gamma spectrometry

Gamma spectrometers are ubiquitous in radioanalytical laboratories primarily due to their ability to simultaneously measure a wide range of gamma emitting radionuclides in samples with relatively little preparation of the sample. For conducting measurements on environmental samples, a number of aspects are worth considering.

Environmental samples often exhibit low levels of contaminant radionuclides or levels that are below detection limits for the instrumental set-up employed. The background gamma spectrum is of prime importance in relation to detection limits, therefore, efforts should be made to reduce the background signal as far as is practicable. Sufficient shielding should be employed and the shielding materials should be such that effective shielding can be achieved without introduction of background signals. Such signals may arise due to contamination of post-1945 lead or steel with trace amounts of fission products, such as cobalt-60, or the existence of significant amounts of lead-210 in 'fresh' lead. Shielding should be optimized such that excessive amounts, which may adversely impact the background, are not used. For low energy analysis, graded internal liners of a few millimetres of copper and tin should be employed to reduce X rays produced within the lead shield proper (see Fig. 15). Active shielding is typically not necessary in environmental measurement laboratories. Efforts should be taken to eliminate as far as practicable or at least stabilize the background due to radon progeny.

The wide range of sample matrices encountered in typical environmental monitoring programmes often engenders a situation where quantification is achieved via the use of energy–efficiency response curves generated for a matrix such as water. In such circumstances, appropriate correction should be applied for samples whose density or composition differs substantially from that of the calibration matrix. This is particularly pertinent for the analysis of radionuclides with energies less than approximately 300 keV. Selection of the geometry for the counting of environmental samples is often based upon increasing efficiency and thereby lowering count time or detection limits. The use of geometries such as Marinelli beakers, however, can increase the probability of true coincidence summation which can lead to significant errors in the measurement of some common radionuclides, such as caesium-134 and cobalt-60, by gamma spectrometry. Attention should be paid to this and appropriate corrections applied. The nature of the sample within the geometry itself can be a source of

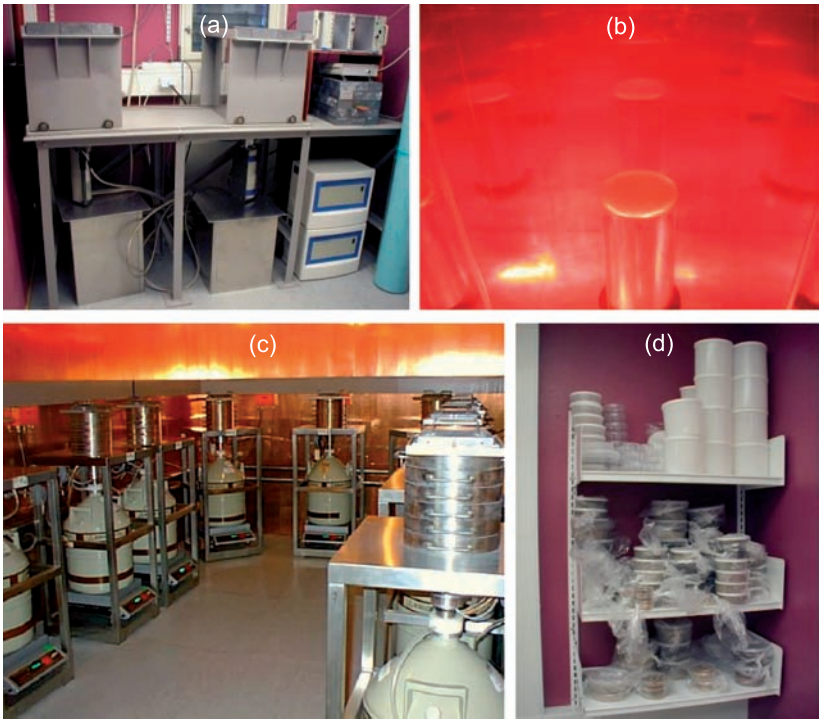

FIG. 15. (a) Electrically cooled HPGe detectors with individual shielding; (b) internal tin–copper shield liners; (c) liquid nitrogen cooled HPGe detectors in a shielded laboratory with tin–copper lining; (d) typical geometries for HPGe measurement of environmental samples. (Source: NRPA.)

error especially when the particle size of the sample is not uniform. Settling of small particle sizes, which may often contain the greatest activity, to the bottom of the counting geometry, can result in significant errors. Measures should be employed to avoid this.

Long count times are characteristic of environmental measurements using gamma spectrometry and correction must be made for decay of the analyte radionuclide, both during the period between sampling and measurement, and over the counting period itself which may be of the order of days.

Lower resolution detectors, such as scintillation based instruments, can be considered where only a limited range of radionuclides is to be measured. For samples containing just one or two radionuclides, NaI(Tl) detectors can offer advantages including being cheaper and somewhat easier to operate. Newer scintillation detectors, such as lanthanum halide types (LaBr, etc.) or cadmium zinc telluride (CdZnTe) detectors, may be of use in situations where a limited

suite of radionuclides is to be analysed, having better resolution than NaI(Tl) based systems (Fig. 16) without the need for liquid nitrogen or other cooling. Sample sizes for analysis with NaI(Tl) spectrometers tend to be larger than for HPGe detectors and are often in the 0.5–1.0 kg range. Samples are most often presented as dried pulverized material in Marinelli beakers, allowing for the detector to be surrounded by an annular sample. Owing to their poor resolution, scintillation based systems tend towards being employed for measurements of samples likely to contain only one or two radionuclides (such as in hospitals) and efficiency calibration is most often conducted using a standard source of the radionuclide of interest in a matrix resembling that of the samples presented. The need for complex corrections, such as should be applied in HPGe based analysis, is therefore reduced.

A large number of excellent guides to the operation of gamma spectrometers are available and the information contained within these is generally applicable to the specificities of conducting environmental measurements. Examples include Refs [203–206].

The selection of which gamma spectrometer to use is a matter of some consequence in environmental measurements. Typically, HPGe detectors are employed which, in the most common form, are useful in the analysis of isotopes

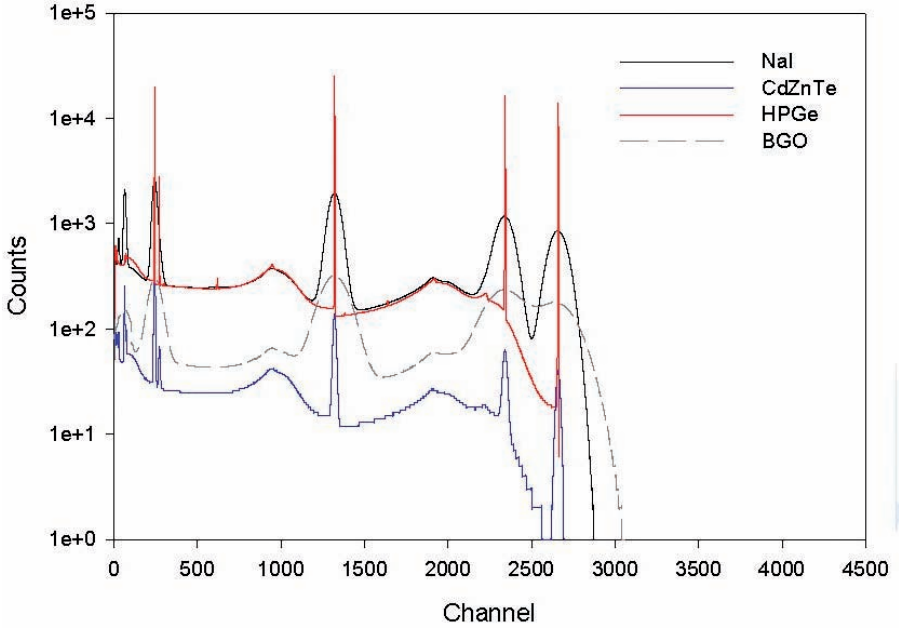

FIG. 16. Comparison of the resolution of HPGe and a range of other commonly encountered gamma detectors.

with energies between 50 keV and 3000 keV. For the analysis of isotopes with lower energies, low energy HPGe detectors may be employed which may extend the useful range down to 10 or 20 keV. The use of large high efficiency or well type HPGe detectors should be carefully considered with respect to the effect of high efficiencies on such factors as coincidence summation.

III.4.3.2. Alpha spectrometry

Alpha spectrometry is the most common method for the determination of alpha emitting radionuclides. Unlike gamma spectrometry, analysis of the spectra produced by typical alpha spectrometers is relatively uncomplicated, as the spectra tend to be simple (see Fig. 17). Preparation of the sample for counting is of prime importance in the analysis of alpha emitting radionuclides. Careful consideration should be given to the radiochemical separation and mounting procedure conducted before the sample is presented to the detector. Appropriate tracers must be employed for the determination of chemical recoveries and must be added and equilibrated with the sample at the earliest practicable point in the radiochemical procedure.

A large number of methods and procedures have been published in the literature regarding the analysis of various alpha emitting radionuclides, and a wide variety of proprietary resins and sorbents are available for the radiochemical separation of analytes from matrices. Analysts should pay careful attention to the selection and implementation of any particular method and ensure that the method is fully validated before being taken into regular use and appropriately tested at regular intervals using relevant intercomparisons and a rigorous quality control system. Appropriate references for the analysis of alpha emitting radionuclides by alpha spectrometry include Refs [207–209].

III.4.3.3. Beta counting and gross beta counters

Analysis of samples for specific beta emitting radionuclides is most often conducted using proportional counters of various types. Gas flow counters exhibit a number of characteristics advantageous to the counting of low levels of activity, including low backgrounds, stability and the ability to employ very thin end windows facilitating the measurement of quite low energy beta radiation. Combined with high efficiencies, these advantages make gas flow counters excellent choices for the analysis of beta emitting radionuclides in environmental samples.

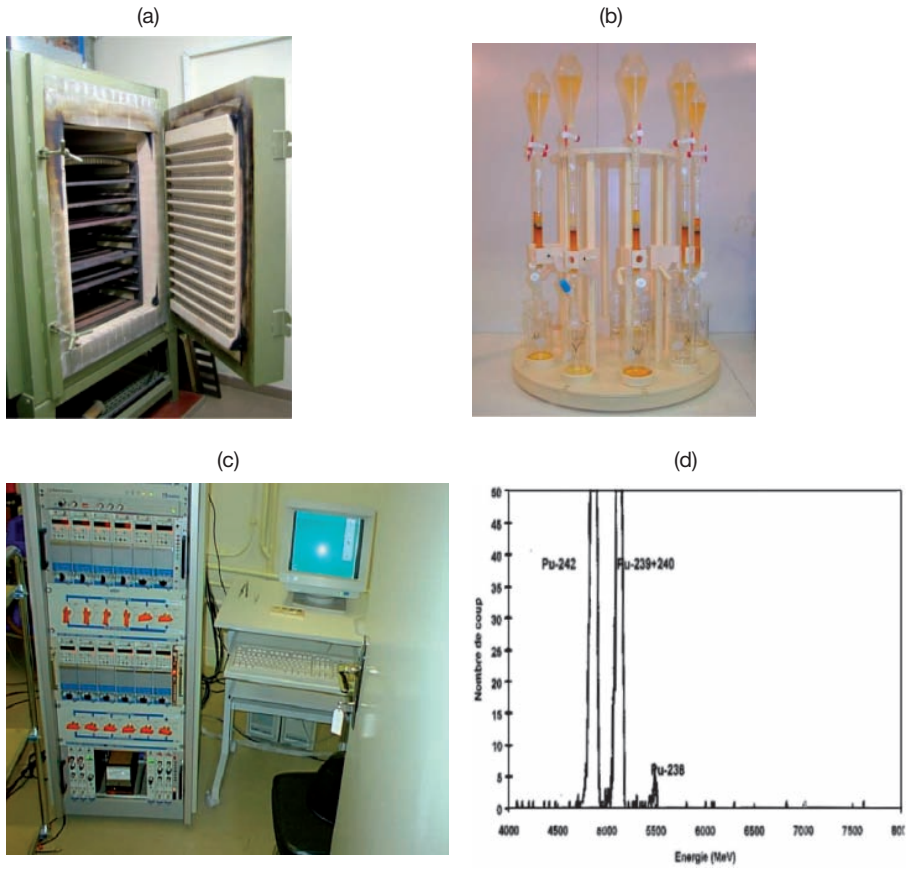

FIG. 17. Steps in the analysis of alpha emitting radionuclides: (a) ashing of samples; (b) radiochemical separation; (c) alpha counting; and (d) spectral analysis.

For the analysis of samples exhibiting typical background levels of beta emitting radionuclides, radiochemical separation of the analyte in question is usually required along with the appropriate use of tracers for determining

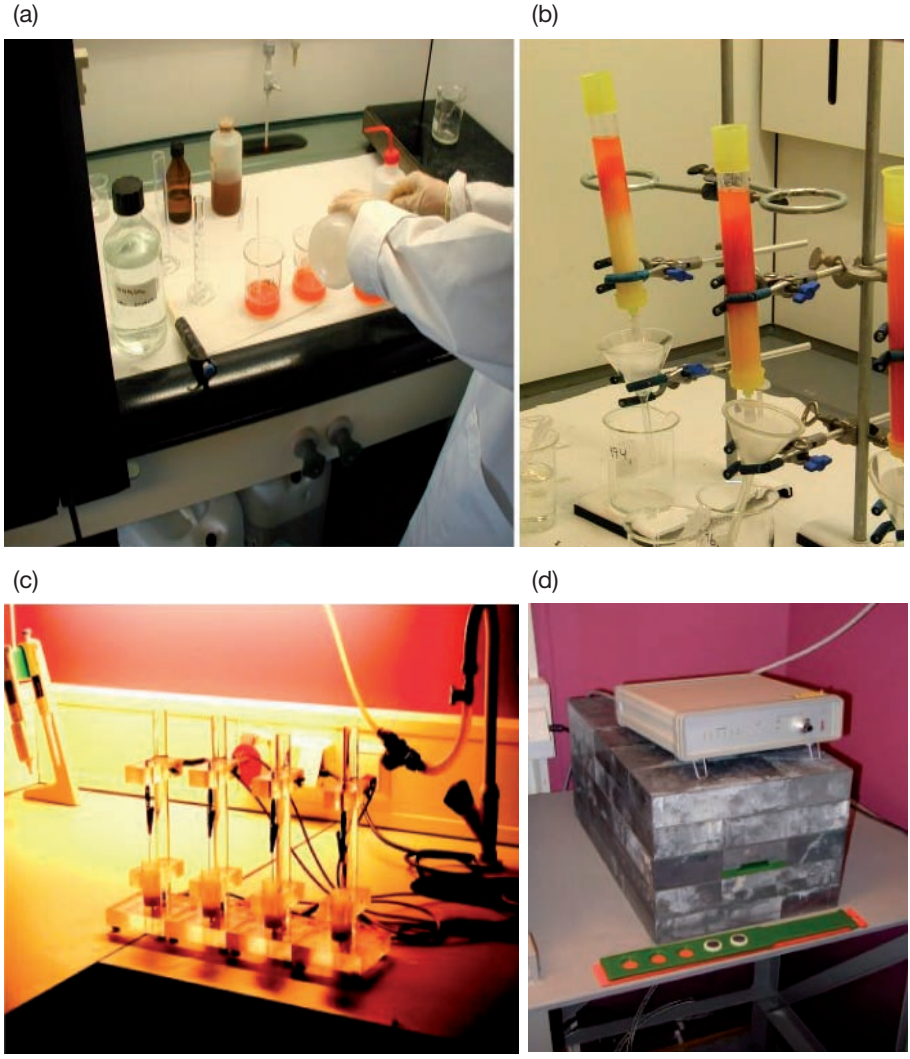

FIG. 18. Analysis of samples for specific beta emitters: (a) dissolution of sample and addition of tracers; (b) separation on ion-exchange resin; (c) electroplating; and (d) counting in a gas flow proportional counter. (Source: NRPA.)

chemical recoveries. The sample is then mounted on an appropriate geometry by any of a number of methods (electrodeposition, evaporation, etc.) before being presented to the detector (Fig. 18).

Gross beta counting may be conducted on a variety of instrument types including proportional counters with alpha/beta discrimination, although GM counters are the most often encountered. Such counters are typically calibrated with potassium-40 sources and samples may be presented for counting in either of two ways. The 'infinitely thick' source is a source of sufficient thickness such that beta particles of any end point energy emitted from below a certain depth in the sample cannot escape. Such samples are typically of the order of 2–3 cm deep and may be packed into suitable cylindrical geometries. Alternatively, a thin source may be presented, minimizing self-absorption in the sample and allowing low energy beta radiation to be counted.

Operation of GM tubes for measurement of environmental samples is a relatively straightforward task although precautions should be taken with respect to sample preparation and calibration sources. Attention should also be paid to determining the plateau region of the detector with respect to high voltage, to ensure stable measurements. Appropriate references for proportional counters, GM tubes and their applications include Refs [210, 211].

III.4.3.4. Liquid scintillation

Most often applied to the determination of low energy beta emitters, such as tritium and carbon-14, some recent advances have extended the usefulness of liquid scintillation to include alpha emitters, such as uranium and plutonium isotopes. Samples for liquid scintillation must usually be dissolved in the scintillator cocktail, although it is sometimes possible to directly count filter papers or powders by simply suspending or dispersing them in the cocktail. The efficiency of liquid scintillation is best for high energy beta emitters such as phosphorus-32. For the analysis of radionuclides, such as tritium or other beta emitters with low end point energy maxima, the absorption of photons before they are detected by the photomultiplier results in a shift of the energy spectrum towards lower values. This effect, known as quenching, is particularly common for environmental samples and correction should be performed experimentally. A number of methods exist for determining the efficiency of liquid scintillation systems and these are fully and appropriately described, along with more extensive information regarding the application of liquid scintillation to environmental measurements, in Refs [186, 212–214].

III.4.3.5. Other methods

A number of other methods for the analysis of environmental samples for radionuclides exist and may be appropriate for the analysis of specific radionuclides as part of an environmental monitoring programme. These include

alpha particle track detectors for radon, various mass spectrometry techniques such as inductively coupled mass spectrometry (ICP-MS) and a wide range of modifications of the basic radioanalytical methods and detectors.

III.5. DETECTION LIMITS

The approximate detection limits of a range of techniques for monitoring liquid discharges are given in Table 14. Those for monitoring airborne discharges are given in Table 15. The approximate detection limits for several gamma emitting radionuclides by HPGe gamma spectrometry using a well shielded detector of 15% relative efficiency are given in Table 16. Table 17 gives the detection capabilities for environmental sample analysis. Table 18 gives the approximate detection limits for iodine-131.

TABLE 14. APPROXIMATE DETECTION LIMITS IN LIQUID DISCHARGE MONITORING

Nuclides	Sampling and preparation	Detectors	Counting time (s)	Approximate detection limit[a] (Bq/L)
λ emitting nuclides	500 mL sample in polyethylene bottle	HPGe 12% relative efficiency	2000	70 (^{51}Cr) 10 (^{54}Mn) 20 (^{59}Fe) 10 (^{58}Co) 10 (^{60}Co) 10 (^{131}I) 10 (^{134}Cs) 10 (^{137}Cs)
Tritium	5 mL sample in 20 mL vial	Liquid scintillation counter	1200	40
β emitting nuclides	10 mL sample dried on 5 cm planchet	Gas flow GM counter	600	40
α emitting nuclides	10 mL sample dried on 5 cm planchet	ZnS(Ag) scintillation counter	600	4

[a] Based on a 3 σ confidence interval.

TABLE 15. APPROXIMATE DETECTION LIMITS IN AIRBORNE DISCHARGE MONITORING

Nuclides	Sampling	Detectors	Counting time (s)	Approximate detection limit[a] (Bq/L)
Noble gases	Flow type chamber vol.: 20 L	50 mm × 50 mm NaI(Tl)	Continuous	10 (^{135}Xe) 70 (^{133}Xe)
		200 mm × 1 mm, plastic	Continuous	10 (^{133}Xe) 2 (^{85}Kr)
		Flow type ion chamber vol.: 10 L, 2 atm.	Continuous	1 (^{133}Xe) 2 (^{85}Kr)
Iodine	Charcoal cartridge 50 L/min, 1 week	HPGe 12% rel. eff.	4000	3×10^{-6}(^{131}I) 4×10^{-5}(^{133}I)
Tritium	Cold trap 50 L/min, 1 month	Liquid SCI. 20 mL vial	1200	2×10^{-2} [b]
Aerosols	50 mm filter paper 50 L/min, 1 week			
λ emitting nuclides		HPGe 12% rel. eff.	4000	7×10^{-6} (^{51}Cr) 1×10^{-6} (^{54}Mn) 3×10^{-6} (^{59}Fe) 2×10^{-6} (^{58}Co) 1×10^{-6} (^{60}Co) 1×10^{-6} (^{134}Cs) 1×10^{-6} (^{137}Cs)
β emitting nuclides (gross)	50 L/min, 1 week	Gas flow M counter	600	7×10^{-7}
α emitting nuclides (gross)	50 L/min, 1 week	ZnS(Ag)	600	7×10^{-8}

[a] Based on 3 σ confidence interval.
[b] Temperature: 50°C, relative humidity: 100%.

TABLE 16. APPROXIMATE DETECTION LIMITS[a] OF SEVERAL GAMMA EMITTING NUCLIDES BY HPGe GAMMA RAY SPECTROMETRY USING A WELL SHIELDED DETECTOR OF 15% RELATIVE EFFICIENCY

Samples	Quantity	Units	^{54}Mn	^{59}Fe	^{60}Co	^{137}Cs	Remarks
Aerosols	10^4 m^3	Bq/m^3	7×10^{-5}	1×10^{-4}	7×10^{-5}	7×10^{-5}	1
Water	20 L	Bq/L	7×10^{-3}	1.5×10^{-2}	7×10^{-3}	7×10^{-3}	2
Soil, sediment	100 g dry	Bq/kg dry	2	4	2	2	3
Agricultural marine products	1 kg wet	Bq/kg wet	0.4	0.8	0.4	0.4	4

[a] Based on a 3 σ confidence interval; counting time 8×10^4 s.

Remarks:

(1) Dust sample on filter paper.
(2) Fresh water is evaporated to dryness; ^{137}Cs is collected from sea water acidified by hydrochloric acid with 10 g of ammonium phosphomolybdate, other nuclides are collected from sea water at pH8.0–8.5 by adding ammonia with 40 g of powdered manganese dioxide.
(3) No treatment applied.
(4) Dried and ashed.

TABLE 17. DETECTION CAPABILITIES FOR ENVIRONMENTAL SAMPLE ANALYSIS

Nuclides	Water		Soil	
	Typical lower limit of detection[a] (Bq/L)	Typical sample volume (L)	Typical lower limit of detection[a] (Bq/kg)	Typical sample mass (g)
^{3}H (HTO)	10	10^{-2}	—	100
^{54}Mn	0.5	10	2	100
^{59}Fe	1	10	4	100
^{60}Co	0.6	10	2	100
^{65}Zn	1	10	4	100
^{90}Sr[a]	0.1	10	2	100
^{95}Zr–^{95}Nb	0.4	10	4	100
^{137}Cs	0.6	10	2	100
^{226}Ra[b]	4×10^{-3}	1	1	1

TABLE 17. DETECTION CAPABILITIES FOR ENVIRONMENTAL SAMPLE ANALYSIS (cont.)

Nuclides	Water		Soil	
	Typical lower limit of detection[a] (Bq/L)	Typical sample volume (L)	Typical lower limit of detection[a] (Bq/kg)	Typical sample mass (g)
^{232}Th[c]	1×10^{-3}	1	1	1
^{238}U[c]	0.1	1	1	1
^{239}Pu[c]	4×10^{-4}	100	0.1	50
^{241}Am[c]	1×10^{-3}	100	0.1	50

[a] The lower limit of detection of gamma emitters will vary according to the number of radionuclides present in the samples.
[b] By radon emanation technique.
[c] After chemical extraction.

TABLE 18. APPROXIMATE DETECTION LIMITS[a] FOR IODINE-131

Samples	Sample form	Detectors	Quantity of samples	Approximate detection limits	Remarks
Aerosols	Charcoal cartridge	HPGe	20 m^3	0.02 Bq/m^3	
Fresh water	AgI	HPGe	1 L	0.4 Bq/L	1
Sea water	AgI	HPGe	5 L	0.04 Bq/L	
Leafy vegetables	Homogenized	HPGe	1–2.5 kg	0.4 Bq/kg	
Milk	Direct	HPGe	2 L	0.2 Bq/L	
	Ion exchanges	HPGe	4 L	0.04 Bq/L	
	PdI_2	LBC	4 L	0.008 Bq/L	2

[a] Based on 3 σ confidence interval, counting time 8×10^4 s.

Remarks:

(1) Iodine is separated, precipitated as AgI and determined by gamma spectrometry.
(2) Iodine is separated, precipitated as PdI_2 and determined by a low background beta counter (LBC).

Appendix IV

EXPOSURE PATHWAYS AND DOSE ASSESSMENTS

An important objective of source and environmental monitoring is the provision of data that permit the analysis and evaluation of doses to the representative person. Environmental monitoring programmes should therefore focus on pathways of human exposure. An exposure pathway defines routes from a source of radionuclides and/or radiation to a target individual or a population, through environmental media. There are two main categories of exposure pathway: pathways that lead to external exposure and pathways; and those that lead to internal exposure. The various exposure pathways of concern are displayed in Fig. 19 [14].

The main external and internal exposure pathways of concern for environmental monitoring are summarized in Table 19 (a, b).

For authorized releases (discharges) and direct external exposure, the exposure pathways are usually stable and well defined. Authorized discharge limits are set or approved by the regulatory body and should take into account the results of the constrained optimization of protection [2, 9].

In order to determine authorized limits at the planning or design stage, consideration should be given to the pathways by which members of the public might be exposed. Furthermore, for the operation of a facility, ongoing consideration will need to be given to the doses that actually are being received. The possible pathways are included in the radioecological model described in detail in Ref. [14]. It was developed to provide simple and generally applicable methods for calculating doses arising from discharges of radionuclides into the environment.

During the operation of a facility, the primary results of source or environmental monitoring programmes and the application of models enable the assessment of internal and external exposures to the representative person. As described in Ref. [30], the protection quantities, equivalent dose and effective dose, are defined as not measurable quantities and their values should be assessed using the results of measurements and modelling:

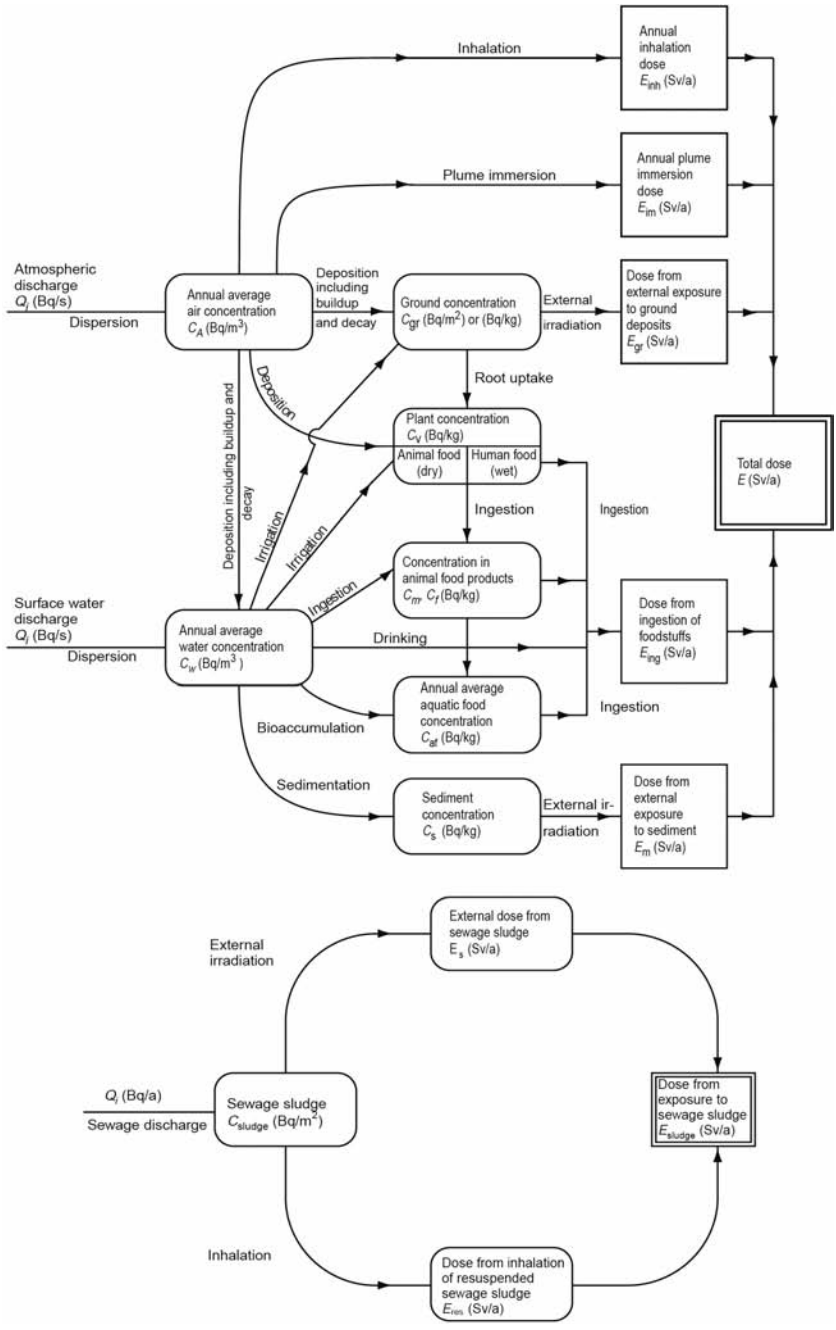

FIG. 19. Possible pathways by which members of the public might be exposed as a consequence of releases of radioactive material from a facility [14].

(a) In the case of external exposure:
   — Measured operational quantities[19], which are defined in ICRU Reports 39, 43, 51, 66 [215–218] and ICRP Publications 74 [219] and 103 [30];
   — Relationship of the protection quantities to characteristics of radiation fields, such as kerma or particle fluence [30];
   — Relationship of the protection quantities to measurable characteristics such as surface (or per volume) activity concentration, spatial distribution of a radionuclide in the environmental medium (e.g. in air, soil and water) [14, 30, 220];
(b) In the case of internal exposure:
   — Relationship of the protection quantities to the intake of a given radionuclide [2, 14, 221–223];
   — Relationships of the protection quantities to the activity concentration of a radionuclide in air, foodstuffs or drinking water;
   — Relationship of the protection quantities to the measured bioassay quantities, such as whole body counter data or thyroid counter data.

For the purposes of radiological protection, the relationships indicated previously are expressed by dose coefficients (or dose functions) and published by the ICRP and ICRU.

Exposure from atmospheric discharges should be estimated, taking into account:

(a) Dispersion of radionuclides in the atmosphere and resulting activity concentrations in the near surface air calculated by means of atmospheric dispersion models;
(b) Dry and wet deposition of radionuclides onto soil and vegetation;
(c) Contamination of plants due to foliar deposition of radionuclides and uptake of radionuclides from soil;
(d) Intake of contaminated feed by domestic animals and the transfer of radionuclides to animal foodstuffs such as milk and meat;
(e) Dose rates due to external exposure from radionuclides in air and radionuclides deposited on the ground;
(f) Location of residence and living habits of the representative persons.

[19] See Definitions.

TABLE 19(a). EXTERNAL EXPOSURE PATHWAYS FOR ENVIRONMENTAL MONITORING[a]

Primary source of exposure →	→Environmental compartment: Processes →	→Type of resulting exposure
External exposure		
Direct radiation from facilities or activities	Air and solid objects (e.g. buildings) between (near by) the source and the reference person: attenuation, scattering, modification of the primary energy spectrum[b]	External exposure
Releases to the atmosphere	Air: atmospheric transport of radionuclides	External exposure from radionuclides in the plume (cloud shine)
	Air: atmospheric transport, including deposition and resuspension of particulate materials	Contact exposure from radionuclides on the skin
	Soil, vegetation (grass, bushes, trees), surfaces of buildings (walls, roof, floors): deposition and resuspension, washout, fixation and movement of radionuclides in the soil, vegetation, etc.	External exposure due to radionuclides deposited on surfaces (ground, buildings, vegetation)
Releases to water bodies	Water: aquatic transport of contaminants	External exposure from radionuclides in water (through swimming, boating, recreation activities, irrigation, etc.)
	Sediments: aquatic transport including processes of sedimentation and resuspension of particulate materials	External exposure due to sediments

[a] This is not, and should not be regarded as, an all-inclusive list.

[b] Attenuation, scattering and modification of the primary energy spectrum should be considered in all cases of external exposure.

TABLE 19(b). INTERNAL EXPOSURE PATHWAYS FOR ENVIRONMENTAL MONITORING[a]

Primary source of exposure →	→Environmental compartment: Processes →	→Type of resulting exposure
Internal exposure		
Releases to the atmosphere or water bodies	Air: atmospheric transport, including deposition and resuspension of aerosols; Water: spreading of radionuclides through aquatic pathways, including contamination of water bodies by atmospheric releases and contamination of underground water; evaporation of tritium	Internal exposure due to inhalation of radionuclides, absorption of tritium through the skin; Internal exposure due to ingestion of contaminated foodstuffs and drinking of water by humans and animals
	Soil and sediments: deposition and resuspension of aerosols, washout and fixation of deposited particles; sublimation of iodine	Internal exposure due to inhalation
	Soil and vegetation: deposition, washout, fixation and movement of radionuclides in soil; deposition, washout and fixation of radionuclides in plants; biokinetic processes in plants and animals, transport of radionuclides in food chains; spreading of contamination in a case of irrigation, etc.	Internal exposure due to ingestion of plant and animal food products
	Rivers, lakes and sea: aquatic transport, transport of radionuclides in food chains; spreading of contamination in the case of irrigation	Internal exposure due to ingestion of fish and seafood, plant and animal food products obtained with the use of irrigation; ingestion of drinking water by humans and animals

[a] This is not, and should not be regarded as, an all-inclusive list.

The assessment of exposures from source monitoring of liquid discharges involves:

(a) Dispersion of radionuclides in water bodies and the estimation of activity concentrations in water;
(b) Transfer of radionuclides to sediments;
(c) Transfer of radionuclides to aquatic foodstuffs (e.g. fish, crustaceans, other seafood);
(d) Use of water as drinking water for humans and animals;
(e) Withdrawal of water from the water body for irrigation of crops;
(f) Living habits of the representative persons (e.g. intake rates, time spent on contaminated sediments).

In Ref. [14], dosimetric and default habit data are provided to estimate exposures to representative persons from results of environmental monitoring programmes, which may provide data on activity concentrations in air, soil, plants, water, sediments and animal products. Dose coefficients for the estimation of effective doses via the following pathways are provided:

(a) External exposure from radionuclides in air ('cloud shine') in Sv/a per Bq/m^3;
(b) Exposure of skin from radionuclides in air in Sv/a per Bq/m^3;
(c) External exposure from radionuclides deposited on the ground ('ground shine') in Sv/a per Bq/m^2;
(d) Inhalation of radionuclides in Sv/Bq;
(e) Ingestion of radionuclides in Sv/Bq.

Default habit data are provided for occupancy at contaminated locations and for the intake of staple foodstuffs. Breathing rates for estimating inhalation doses are also given.

The model approaches and the default data sets given in Ref. [14] are intended for estimating exposures for screening purposes. Due to the design of the model, the parameters recommended and the assumptions applied, the model should provide (in general) conservative estimates of exposures. Even under very specific circumstances, it is considered to be unlikely that the model underestimates real doses by more than a factor of 10.

For emergency releases, the contributions of different pathways to the doses received by workers and the public may be substantially different from the normal pathways and they may be subject to a pronounced seasonality, i.e. both the absolute and relative contribution may depend largely on the season during which the emergency occurs. After single inputs of radionuclides, dose

rates and activity concentrations in environmental media are subject to a pronounced time dependence due to radioactive decay, loss of radionuclides from surfaces, plant growth, and metabolism in animals, biokinetic and other processes. These differences should be considered when establishing an emergency monitoring programme. In order to protect the public and workers from deterministic health effects following major accidents, radiological criteria may be applied in emergencies different from those applied under conditions of normal discharges and, therefore, the collection of additional monitoring data may be required.

During different phases of an accident, the exposure pathways may change and different monitoring data may be necessary to support decision making regarding protective actions. Thus, at an early stage of an accidental atmospheric release, the monitoring should be focused on measurements of exposure due to cloud shine and on the sampling of radionuclides from the plume itself in order to assess the contributions of external exposure and inhalation to radiation doses. Once the release has been terminated and the radioactive cloud has passed, monitoring should be refocused towards 'ground shine' and food contamination, to assess the contributions of external exposure and ingestion to doses.

In existing exposure situations, exposure pathways are usually well defined and unlikely to change rapidly. External exposure is determined by the radiation from radionuclides deposited on the ground or sediments, building surfaces or vegetation, and not by cloud shine. The ingestion of agricultural and/or natural foodstuffs containing radionuclides may contribute substantially to internal exposure. Because of the migration of long lived radionuclides into deeper soil layers, the importance of both the resuspension and, therefore, the inhalation exposure pathway, decreases with time.

Usually, the evaluation of the radiological significance of an emergency situation can be based on both monitoring data and model predictions (and any combination of both). However, especially in the beginning, only a few monitoring measurements will be available, in a limited spatial and temporal resolution.

Therefore, it may be difficult to evaluate the radiological situation based on monitoring data alone. On the other hand, results of radioecological models concerning radiological consequences are associated with uncertainty, mainly due to the pronounced time dependence immediately after the emergency and due to incomplete knowledge of the parameters for both, describing the radionuclide transport in the environment and characterizing living habits and agricultural practice.

During all phases of the emergency, the consistency check of measured data is a key issue for all monitoring programmes. For this purpose, relationships of radionuclide concentrations in environmental media (e.g. deposition to the

ground and concentration in feed or foodstuffs) should be analysed. However, such validation requires a minimum of measurements.

To facilitate such consideration, radioecological models that predict the radionuclide transfer in the environment, the resulting doses and the possible effect of mitigating actions can be very important for emergency management. If large areas are radioactively contaminated, current and future contaminations of agricultural and urban areas, and of foodstuffs, are of special concern. The successful modelling may be needed to complement or interpolate measured data or to convert them into quantities required for dose assessment. Furthermore, future developments of the radiological situation can only be evaluated using the predictive capabilities of models. Additionally, benefits and costs of countermeasures in a specific emergency situation can only be estimated and compared with other options by means of appropriate simulation models.

Dose assessment based on models may use monitoring data, results from atmospheric or aquatic dispersion models or a combination of both, monitoring data and model results. The combination of both, monitoring and modelling results, is usually referred to as data assimilation. Details on techniques of data assimilation in radiological consequence assessment are given in Ref. [224]. Such techniques should be based on robust approaches, since erroneous measurement data or user input may occur at any time.

Both external and internal exposures can be assessed either with appropriate measurements or with dose assessment models. However, measurements of external dose rates only allow the assessment of potential exposures of individuals spending all the time at the location for which the dose rates are known. So, estimation of realistic exposures requires the use of dose assessment models. Also, future external exposure can only be based on information about radionuclides deposited on the surface in the environment. However, external dose rates are the result of a complex interaction of surface contamination, decay properties of the radionuclide, exposure geometry and shielding.

Dose assessments based on gamma dose rate measurements alone depend largely on the representativeness of the measurement in respect of the temporal and spatial resolution. In any case, specific techniques for interpolation in time and space are required for realistic dose estimations.

Assessments of external radiation exposures in settlement areas are especially complex due to the dependence of the exposure on a number of factors that are characterized by large variabilities in time and space, such as the relative deposition on different surfaces, the exchange of activity between the surfaces, type and structure of buildings and plants, and living habits of the population.

Many models are relatively simple since they are designed for estimating average doses for large areas. However, recently significant research has been carried out on dispersion and deposition of radionuclides and the resulting exposure of people in urban areas [225, 226].

Assessment of internal exposure may be based either on measurements or on dose assessment models. Direct measurements of incorporated radionuclides are difficult to obtain, but WBC measurements or measurements of the thyroid enable a determination of the body or organ burden by gamma emitting radionuclides. Such data are input into biokinetic dosimetric models for estimating resulting internal exposures.

For assessing the potential exposure of the population from ingestion of contaminated foodstuffs, radioecological models are valuable tools. Various dynamic radioecological models (BIOMOVS, VAMP, BIOMASS) have been developed in the past few decades and tested in several international studies [227–230]. As for models developed for the estimation of exposures during routine discharges, radioecological models for emergencies cover the transfer of radionuclides in the environment. Input is the dry and wet deposition. End points are the time dependent and time integrated activity concentrations in soil, foodstuffs and feedstuffs, and the activity intake by humans and resulting exposures. Such models need to be flexible enough to take into account the seasonality of transfer processes and to be adapted to a wide range of environmental and societal conditions.

In Germany, in reaction to the Chernobyl accident, the dynamic radioecological model ECOSYS [229] has been developed for estimating time dependent activities in feeds and foods, and to assess exposures of reference population groups subsequent to single depositions of radionuclides. The model takes into account internal exposure via inhalation and ingestion; furthermore, it calculates external exposure from the passing cloud and from radioactivity deposited on the ground. In its original version, the site specific parameter values of the model are typical for agricultural conditions in southern Germany. The ingestion dose is calculated as a function of time, considering 18 plant species, 11 animal food products and 18 processed products. The ingestion and inhalation exposures are estimated for six age groups using age dependent consumption and inhalation rates and age dependent dose factors. The model has been integrated into various national and European real time decision support systems (e.g. ARGOS [231] and RODOS [232]) that are designed for the management of large scale radioactive contaminations.

In the case of a nuclear emergency, the results of radioecological modelling are inherently associated with uncertainties, due to variability of the model parameters and incomplete knowledge of the exposure conditions.

During and after the emergency, models and model parameters can be improved significantly if data are determined during monitoring that characterize the whole transfer of radionuclides through the food chain. In practice, this could be achieved by monitoring the contamination of different environmental samples — soil, grass, milk, etc. — at the same place and time. This strategy is one promising way of obtaining such complete data sets. Currently, this idea is not widely accepted, but it should be kept in mind for the (further) development of monitoring to obtain the highest possible benefit from monitoring measurements.

Appendix V

CHARACTERIZATION OF THE SIZE AND BIOLOGICAL SOLUBILITY OF RADIOACTIVE AEROSOLS

The radiation dose resulting from inhalation of any radionuclide substantially depends upon its physical and chemical form. In order to calculate a protection quantity 'effective dose', the ICRP assigned numerical values to a wide range of parameters of biokinetic and dosimetric models. These models and values are known as reference models and values, and reference values were chosen to be typical.

In any particular situation, the actual values of many of the parameters may be different from the reference values. In Ref. [18] the ICRP highlights that a value of effective dose is defined for the reference person, which is described by a set of body related reference values (worldwide generalized and averaged properties of the human body, such as gender, age, body mass and physiological parameters). The body related reference values, i.e. the parameters of the reference person, shall not be modified in any circumstances.

The assessments of the effective dose may, however, take into account the facility specific exposure conditions. The biological solubility of inhaled or ingested radioactive materials determines the absorption rate of the radioactive material in the respiratory and alimentary tracts, and could be characterized by the parameters 'type of materials' and 'gut transfer factor' (see Definitions). Airborne radionuclides may be present in gas or vapour form or, more commonly, associated with liquid or solid particles. The behaviour of an airborne particle depends on its size, shape and density. The parameters of the aerosol size distribution are important for adequate assessments of the atmospheric dispersion and for dose assessments. In atmospheric transport, the size of aerosol particles determines the velocity of sedimentation and resuspension of aerosols to/from the ground; in dosimetric assessments, the size of aerosol particles is a main parameter for assessment of the pattern of aerosol deposition in the respiratory tract (of a reference person).

The identification of such facility specific reference values as parameters of the aerosol size distribution of the type of materials, and the gut transfer factor could be important if there are indications that assessments with the default reference values lead to substantially biased assessments of the effective dose.

TABLE 20. ANNUAL DOSE PER UNIT CONTENT OF RADIONUCLIDE[a] IN AIR, $SvBq^{-1}m^3$ *(adult reference person, member of the public[b])*

	AMAD (AMTD) (μm)		AMAD (μm)	
Radionuclide, type of materials, gut transfer factor	0.03 (0.016)	0.1 (0.059)	1	10
^{60}Co, type M, $f_1 = 0.1$	3.2E-04	1.7E-04	8.2E-05	4.5E-05
^{60}Co, type S, $f_1 = 0.01$	1.0E-03	5.9E-04	2.5E-04	9.2E-05
^{90}Sr, type F, $f_1 = 1$	5.1E-04	2.8E-04	1.9E-04	2.2E-04
^{90}Sr, type M, $f_1 = 0.1$	1.1E-03	6.2E-03	2.9E-04	1.3E-04
^{90}Sr, type S, $f_1 = 0.01$	5.4E-03	3.1E-03	1.3E-03	3.6E-04
^{239}Pu, type M, $f_1 = 0.005$	1.6E+00	9.3E-01	4.1E-01	1.9E-01
^{239}Pu, type S, $f_1 = 0.00001$	6.0E-01	3.3E-01	1.3E-01	5.6E-02

[a] Selected radionuclides, aerosol AMTD/AMAD and types of materials. Dose coefficients for other radionuclides and characteristics of aerosols could be calculated from the data in Ref. [233].

[b] The reference volume of daily inhaled air is 22.2 m^3; inhalation during a year.

Table 20 gives examples of the dose coefficient 'annual dose per unit content of radionuclide in the air' for several important radionuclides, different activity median aerodynamic diameter (AMAD) or activity median thermodynamic diameter (AMTD) and different type of materials.

The ICRP adopted a default AMAD of 1 μm in 1995 for the estimation of public exposure (see Ref. [234], para. 181). A review of Dorrian and Bailey [235] of 160 sets of measurements in 52 papers in the open literature supported the choice of this value. However, this default value is intended to be deliberately realistic rather than conservative. As such, it needs to be treated with caution as AMADs smaller than 1 μm and up to 18 μm have been measured [235]. Most measured values fell into two categories: aerosols released into the atmosphere by the Chernobyl accident, and those produced by resuspension of radioactive material deposited on the ground or released into the sea. The distributions of measured AMADs for each category were well fitted by single log-normal with median values of 0.6 and 6 μm, respectively. A review [236] of the characterization of hot particles released into the environment showed a wide spectrum ranging between 0.5 μm and 150 μm and, depending on the location, the time and the collection of particles after the Chernobyl accident.

A comprehensive review similar to that of Dorrian and Bailey [235], but of particle size distribution measurements in discharges, does not appear to be available. Nevertheless, examples of such data are reported in the open literature [237–241]. Malátová et al. [237] and Rulík et al. [238] report AMADs between 0.9 μm and 3.6 μm in the ventilation stack at the V1 nuclear power plant, Jaslovské Bohunice, Slovak Republic (PWR Novovoronez VVER 440, Type 230). Mahoney et al. [239] reviewed measurements made in the ventilation exhaust of the Plutonium Finishing Plant of the US Department of Energy's Hanford Project. AMADs in the range 3.3–9.0 μm were measured, with the observation that some of the sampled material had the appearance of rust. Thus, some of the collected material was postulated to have originated from accumulated deposits on the interior surfaces of the ventilation ductwork flaking off and being re-entrained in the discharge flow. Ström [240] reported AMADs of approximately 10 μm "with wide variations" in the ventilation stack of a boiling water reactor. Kenoyer [241] conducted measurements from the PR stack (296-A-1) for the Westinghouse Hanford Company using cascade impactors and a laser spectrometer. However, it was not possible to define AMADs for the sampled particles, as significant quantities of material were collected on the impactor pre-separator (>10 μm aerodynamic diameter). Nevertheless, the results indicated that the larger sampled particles originated from the flaking of accumulated material within the system. It should be noted that the majority of reviewed papers refers to measurements with cascade impactors, which have physical limitations in the submicron area and which are not capable of identifying the size of ultrafine particles.

The described examples illustrate the difficulty in assigning typical or indicative particle size distributions to an individual discharge stream, especially as the size distribution appears to be not only a function of the process discharge penetrating the filtration system, but also of the nature of the accumulated material within the system downstream of the filters. The accumulated material is likely to be a complex mixture, depending upon the age of the system, the number and type of process discharges released through it, and the prevailing conditions (e.g. temperature, humidity, flow rate) within the system. It would be very difficult to predict the size and number of particles shed for this material, and this only serves to emphasize the need for measurements of the discharged particle size distribution, wherever possible. It would be important, wherever possible, to measure particle size distributions in order to provide realistic parameters for use in radiation dose estimates. While a default value AMAD would have some value, an actual measurement of the discharge particle size distribution is needed to provide the source term for realistic dose estimates.

A wide range of methods of measuring particle size has been developed (see Ref. [242]) based on various particle properties, including light scattering power and dynamic behaviour. General guidance on the measurement of airborne

particle size distributions is available from a number of sources [243–246]. In general terms, these methods can be subdivided into those which measure particle size distribution with and without physically collecting a sample of the material. Those that do not collect a physical sample are probably less suitable for this application, as their measurements will comprise all airborne particles, whether they are radioactive or not. Measurement methods that collect a physical sample are more suitable, as the collected material is available for subsequent laboratory analysis (either gross activity or radionuclide specific activity).

On this basis, the most commonly used methods would be the cascade impactor, cascade cyclone or cascade centripeter. Each device separates and collects the sampled particles according to their aerodynamic diameter. The choice of which to use is dependent upon the particular sampling situation, but the following features should be considered. The collection stages of an impactor can become overloaded with material, resulting in a change in their collection characteristics accompanied by the possibility of previously collected material becoming airborne again and being captured by subsequent collection stages. Precautions are also necessary to prevent particles bouncing off the collection surface. Cyclones are able to accommodate more material than impactors, but their collection characteristics are shallower than those of impactors, with the resulting poor size resolution. Centripeters can also accommodate more material than impactors and are less prone to particle bounce. A cascade impinger would be appropriate if collection into a liquid medium were required.

Whichever device is chosen, the basic requirements of any measurement are to collect:

(a) A representative sample;
(b) Sufficient material to satisfy the sensitivity of the subsequent analysis.

The means of acquiring a representative sample are as described for continuous or intermittent sampling (see Appendix II):

(a) Sampling from a suitable location;
(b) Sampling isokinetically and minimizing deposition in the sampling nozzle;
(c) Minimizing transport losses of the sampled material before collection.

The precautions and sampling location assessments described in Appendix II and the guidance contained in Refs [49, 50, 247] are equally relevant to the particle size distribution measurements described here. However, particle size distributions measured at a well characterized and suitable sampling location near the base of a stack may not be entirely representative of the particle size distributions emitted from the stack, due to the potential for vertical elutriation

within the stack. Larger particles may have sufficient terminal settling velocities to settle in the stack against the discharge flow. In this case, if the measured particle size distributions are used in the source term for dose estimate calculations, then the resulting estimates may be conservative. Nevertheless, measuring the particle size distribution at such a convenient location may be considered an acceptable compromise.

The range of dose coefficients given in Table 21 for different types of materials demonstrates that the biological solubility ('type of materials') of radioactive aerosols is an important factor, which should be carefully considered in dose assessments. In most cases, the appropriate information could derive from knowledge of the physical and technological processes, which generate the radioactive aerosols and from the data published elsewhere about biological solubility of aerosols with radionuclides in specific chemical forms [234].

If a facility operates with a rare physical or chemical form of the radionuclide, or in the case of an accident with substantial inhalation doses, experimental characterization of the biological solubility could be justified. Nevertheless, such a characterization would require substantial time, very specific experimental facilities, and high skill and knowledge of the experts involved. Detailed guidance about appropriate methods and equipment for these purposes is given in Ref. [242].

Appendix VI

EXAMPLES OF RESULTS OF SOURCE AND ENVIRONMENTAL MONITORING PROGRAMMES

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), since its inception in 1955, has issued 15 authoritative reports (all UNSCEAR reports are available from http://www.unscear.org/unscear/en/publications.html), which include fundamental reviews of sources of ionizing radiation, levels of releases of radioactive materials to the environment, and associated doses to the public for different types of nuclear facilities and activities. The UNSCEAR 2000 Report, Sources and Effects of Ionizing Radiation [248], is the most recent publication with such a review. The IAEA's on-line database, DIRATA (http://dirata.iaea.org/) [249], contains IAEA Member States' official records about annual radioactive discharges of nuclear facilities. The IAEA's on-line Marine Information System (MARIS) covers the distribution of radioactive and stable isotopes in the marine environment (http://maris.iaea.org/). The generalized results of large scale environmental monitoring programmes after the Chernobyl accident can be found in Refs [250, 251], and the results of environmental monitoring in the seas around the Russian Federation are given in Ref. [252].

This appendix gives several examples of results of source and environmental monitoring. The examples are more or less arbitrarily chosen. They are not, and should not be regarded as, typical or all-inclusive.

Figures 20 and 21 show the annual atmospheric discharges of the German nuclear power plants Biblis A and ISAR 2, since they began operating in 1974 and 1988, respectively. The real discharges, which are given in the legends of the figures, are well below the authorized discharges at all times.

Annual discharges are input for estimating annual exposures. Figure 22 shows the dose estimates for adult reference persons in the vicinity of German nuclear power plants from 1990 to 2006. Typically, the annual effective doses are below 5 μSv/a. The assessments are made with the model that has to be used for licensing of facilities that discharge radionuclides to the environment [254]. The assessments are made for the location with the highest contamination in the vicinity of the nuclear power plants. They include inhalation, ingestion and external exposure from the cloud and from the ground. Shielding effects by buildings are not taken into account. All food consumed is assumed to be produced locally at the location where the highest contamination of plants is expected. Intake rates are approximately a factor of 2 higher than the national

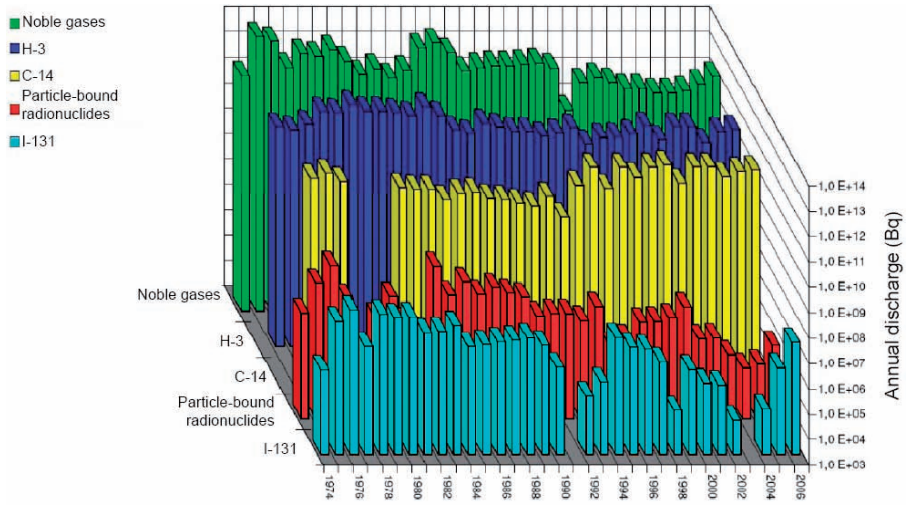

FIG. 20. Annual atmospheric discharges of the Biblis A nuclear power plant (Germany) since it began operation. The authorized discharge limits are: 10^{15} Bq/a for noble gases, H-3 and C-14, respectively; 3.7×10^{10} Bq/a, and 8.5×10^{9} Bq/a, for particle-bound radionuclides and I-131, respectively (modified from Ref. [253]).

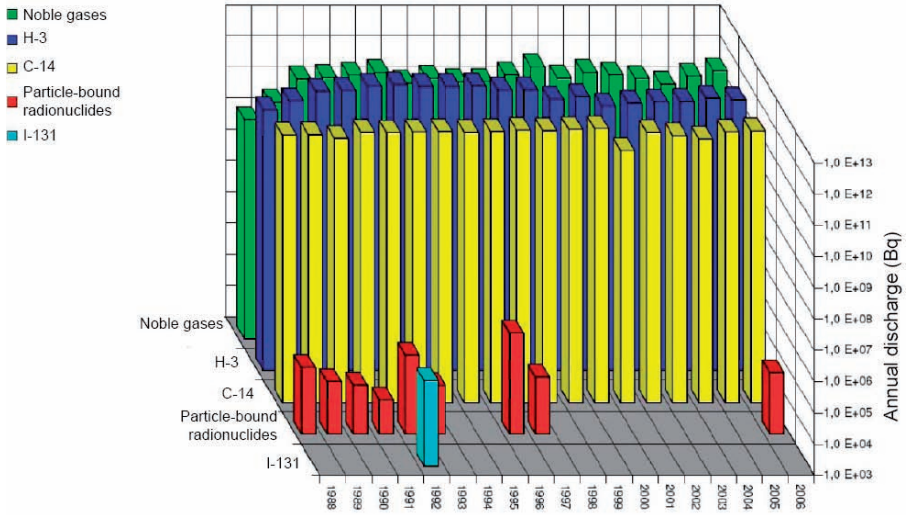

FIG. 21. Annual atmospheric discharges of the ISAR 2 nuclear power plant (Germany) since it began operation. The authorized discharge limits are: 10^{15} Bq/a for noble gases, tritium and C-14, respectively; 3.0×10^{10} Bq/a, and 1.1×10^{10} Bq/a for particle-bound radionuclides and iodine-131, respectively (modified from Ref. [253]).

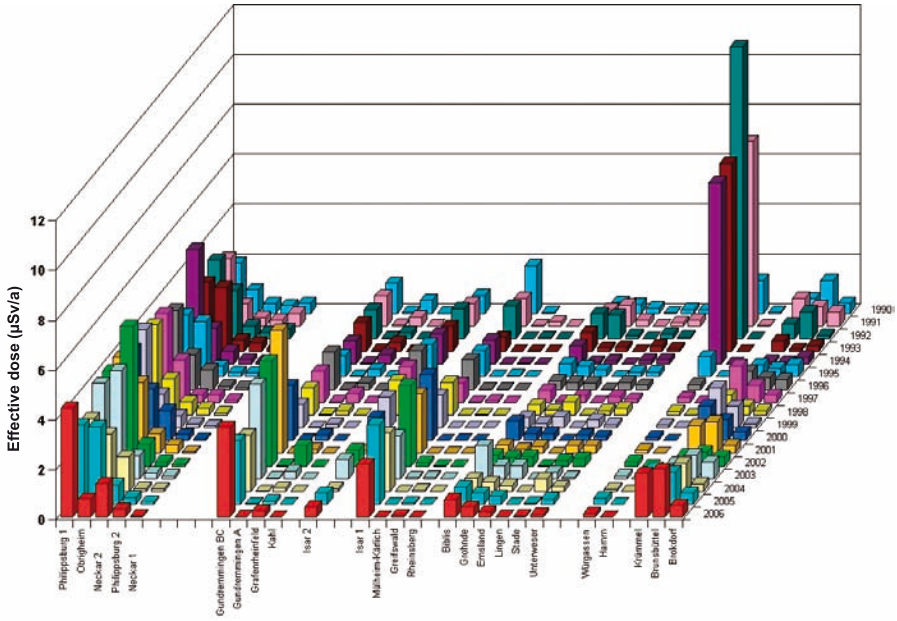

FIG. 22. Annual effective doses to adults due to atmospheric discharges from all German nuclear power plants from 1990–2006 (modified from Ref. [253]).

average to avoid an underestimation of real doses. In general, these assumptions are very atypical for real persons, so the results can be considered conservative.

Figure 23 shows the results of carbon-14 monitoring in the vicinity of the Philippsburg nuclear power plant (Germany) for the years 1983 and 1984 [255]. The values are given as 'ΔC-14 values', which are defined as the excess carbon-14 in per mille above a standard of the year 1950. During the last 10 000 years, ΔC values varied from +150 (about 9000 B.C.) to 20 (500 A.D.). Due to atmospheric weapons tests, atmospheric ΔC-14 values increased in the northern hemisphere to values of up to 1000. Until 1990, ΔC-14 values dropped to about +200. The increase in the carbon-14/carbon-12 ratio in the wind direction can be clearly observed.

A summary of discharges of iodine-131 to the environment is shown in Fig. 24. It compares the integrated iodine-131 inventory discharged with patients who leave hospital after iodine-131 treatment for therapeutic and diagnostic reasons, the liquid discharges of iodine-131 from hospitals, and airborne discharges from nuclear power plants (modified from Ref. [253]).

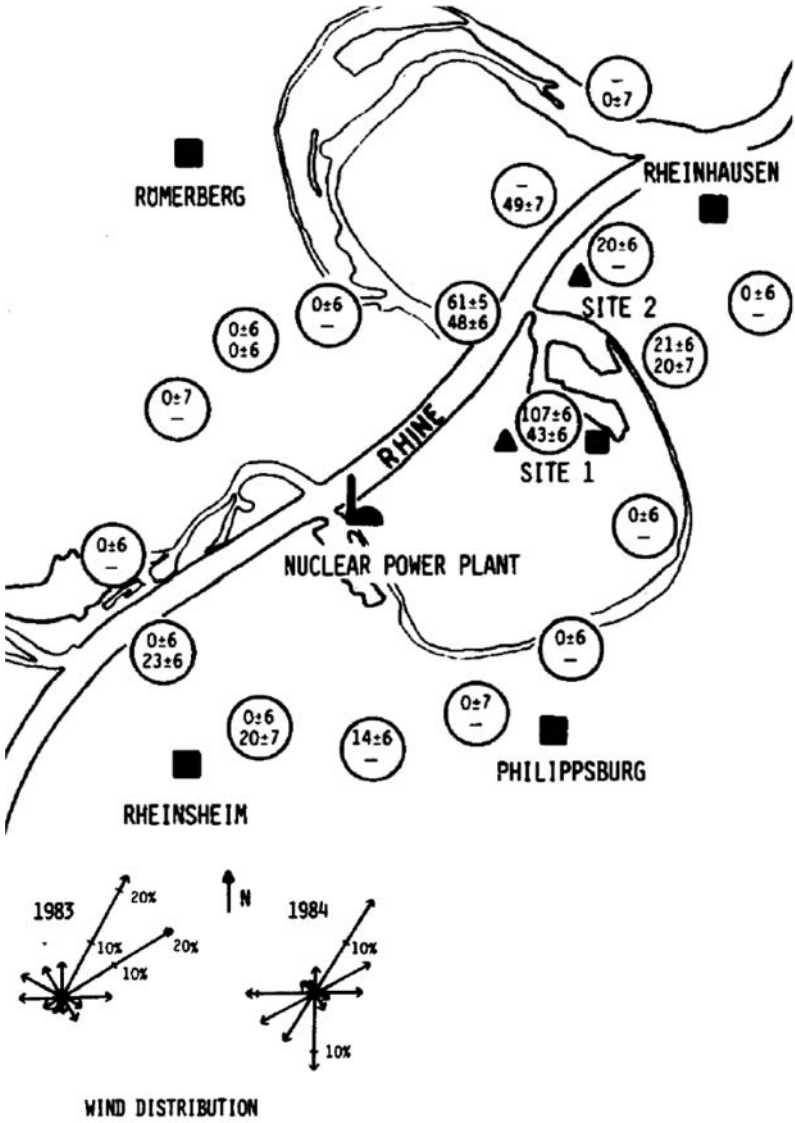

FIG. 23. Results of carbon-14 monitoring of tree leaves in the vicinity of the Philippsburg nuclear power plant (Germany) in the years 1983 (upper value in the circle) and 1984 (lower value in the circle). The distributions of wind direction during the growth periods in 1983 and 1984 are also given (from Ref. [255]).

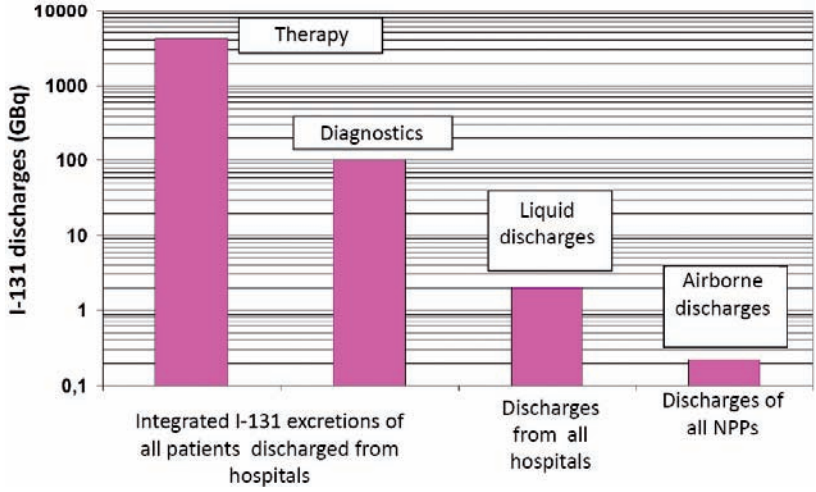

FIG. 24. Comparison of iodine-131 discharges in 2000 to the environment from several sources in Germany. The total activity inventory in patients discharged from hospital is compared with liquid iodine-131 discharges from all hospitals and the airborne discharges of iodine-131 from nuclear power plants [253].

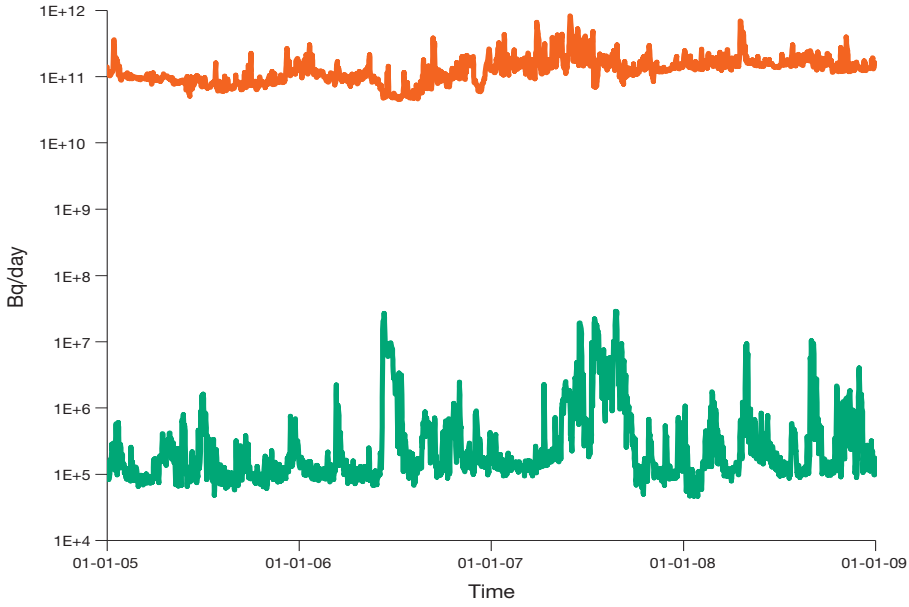

FIG. 25. Results of discharge monitoring at the ventilation stacks of the Rovno nuclear power plant (Ukraine): total daily discharge of noble gases (red line) and radioiodines (green line) during 2005–2008 from two PWR-440 units and two PWR-1000 units. (Data provided by the Rovno nuclear power plant.)

An example of the time frame of the discharges of noble gases and radioiodines to the atmosphere from four power units of the Rovno nuclear power plant (Ukraine) is given in Fig. 25. The fluctuations of the daily discharged activity are associated with modifications in the operational status of power reactors and the highest levels usually observed during maintenance periods.

An example of results of the large scale monitoring programme after the accident at the Chernobyl nuclear power plant is presented in Table 21. Major releases continued for 10 days. The total release of radioactive substances was about 14 EBq[20], which included 1.8 EBq of ^{131}I, 0.085 EBq of ^{137}Cs, 0.01 EBq of ^{90}Sr, and 0.003 EBq of radioisotopes of plutonium. The noble gases contributed about 50% of the total release. Radionuclides in the releases from the stricken reactor were in the form of gases, condensed particles and fuel particles. The presence of the latter was an important characteristic of the accident. Oxidation of nuclear fuel was the basic mechanism of fuel particle formation. During oxidation and dispersal of the nuclear fuel, volatilization of some radionuclides took place. After the initial cloud cooled, the more volatile of the released radionuclides remained in the gas phase, while the less volatile condensed on particles of construction materials, soot and dust.

Radioactive compounds with relatively high vapour pressure (primarily isotopes of inert gases and iodine in different chemical forms) were transported in the atmosphere in the gas phase. Isotopes of refractory elements (e.g. cerium, zirconium, niobium, plutonium) were released into the atmosphere primarily in the form of fuel particles. Other radionuclides (isotopes of caesium, tellurium, antimony, etc.) were found in both fuel and condensed particles. Fuel particles made up the most important part of the fallout in the vicinity of the release source. Further details of the accident and monitoring data are available from Refs [248, 250, 251, 256].

[20] 1 EBq (exabecquerel) = 10^{18} Bq.

TABLE 21. COMPOSITION OF THE TOTAL RELEASE OF PRINCIPAL RADIONUCLIDES DURING THE CHERNOBYL ACCIDENT [250]

Group	Radionuclide	Half-life	Activity released (PBq)[a]
Noble gases	^{85}Kr	10.72 a	33
	^{133}Xe	5.25 d	6500
Volatile elements	^{129m}Te	33.6 d	240
	^{132}Te	3.26 d	~1040
	^{131}I	8.04 d	~1760
	^{133}I	20.8 h	910
	^{134}Cs	2.06 a	~47
	^{136}Cs	13.1 d	36
	^{137}Cs	30.0 a	~85
Elements with intermediate volatility	^{89}Sr	50.5 d	~115
	^{90}Sr	29.12 a	~10
	^{103}Ru	39.3 d	>168
	^{106}Ru	368 d	>73
	^{140}Ba	12.7 d	240
Refractory elements (including fuel particles)	^{95}Zr	64.0 d	84
	^{99}Mo	2.75 d	>72
	^{141}Ce	32.5 d	84
	^{144}Ce	284 d	~50
	^{239}Np	2.35 d	400
	^{238}Pu	87.74 a	0.015
	^{239}Pu	24 065 a	0.013
	^{240}Pu	6 537 a	0.018
	^{241}Pu	14.4 a	~2.6
	^{242}Pu	376 000 a	0.00004
	^{242}Cm	18.1 a	~0.4

[a] 1 PBq (petabecquerel) = 10^{15} Bq.

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DEFINITIONS

The following definitions apply for the purposes of the present report only.

accreditation. A procedure by which an organization or individual laboratory is officially recognized as having the capability to perform certain measurements or analyses reliably and with adequate accuracy and precision.

aerosol. A suspension of solid or liquid particles in a gas.

aerodynamic diameter (of an airborne particle). A diameter that a sphere of unit density would need to have in order to have the same terminal velocity when settling in air as the particle of interest.

thermodynamic diameter (of an airborne particle). A diameter that a sphere of unit density would need to have in order to have the same diffusion coefficient in air as the particle of interest.

activity median aerodynamic diameter (AMAD). The value of aerodynamic diameter such that 50% of the airborne activity in a specified aerosol is associated with particles smaller than the AMAD, and 50% of the activity is associated with particles larger than the AMAD.

(Note: The AMAD is used for particle sizes for which deposition depends principally on inertial impaction and sedimentation (i.e. typically those greater than about 0.5 μm). For smaller particles, deposition typically depends primarily on diffusion, and the ***activity median thermodynamic diameter (AMTD)*** *— defined in an analogous way to the AMAD, but with reference to the thermodynamic diameter of the particles — is used.)*

type of materials (lung absorption type). A classification used to distinguish between the different rates at which inhaled radionuclides are transferred from the respiratory tract to the blood.

(Note: Reference [234] classifies materials into three major lung absorption types:

(a) *Type F (fast) are materials that are readily absorbed into the blood;*

(b) *Type M (moderate) are materials that have intermediate rates of absorption into the blood;*

(c) *Type S (slow) are materials that are relatively insoluble and are only slowly absorbed into the blood;*

(d) *Type V (very fast absorption) deposited materials that, for dosimetric purposes, are assumed to be instantaneously absorbed into body fluids from the respiratory tract: applied only to certain gases and vapours.*

The compound specific characterization of material is also used by the ICRP. See also 'gut transfer factor', a similar concept for the human alimentary tract.)

annual dose. The dose due to external exposure in a year plus the committed dose from intakes of radionuclides in that year.

atmospheric dispersion. See dispersion.

contamination. Radioactive substances on surfaces, or within solids, liquids or gases (including the human body), where their presence is unintended or undesirable, or the process giving rise to their presence in such places. The term contamination refers only to the presence of radioactivity, and gives no indication of the magnitude of the hazard involved.

count. The signal indicating that an ionization event has been detected.

counter. A general designation applied to radiation detection instruments that detect and measure radiation.

proportional counter. A modified ionization chamber in which a higher voltage is impressed, making the electric field near the axial wire intense enough to accelerate the approaching electrons to energies so high that their collisions with the gas molecules cause further ionization.

(Note: This effect, called gas multiplication, makes the output electric pulse proportional to the ionization produced by the radiation entering the counter and thus permits differentiation among particles of various kinds and energies.)

Geiger–Müller (GM) counter. A modified ionization chamber, results from the application of a still-higher voltage across the electrodes of a proportional counter.

(Note: Individual particles of various kinds and energies entering a Geiger–Müller counter produce essentially the same large output pulse, making the instrument an excellent counter of individual particles. The mixture of gases within a Geiger–Müller counter

quenches the avalanche of ions produced by a single particle of radiation so that the device can recover to detect another particle.)

whole body counter (WBC). A counter that measures the activity of radionuclides inside the human body.

(Note: The WBC is only applicable to radioactive materials that emit gamma rays, although in certain circumstances, beta emitters can be measured also.)

decision quantity. A random variable for the decision whether the physical effect to be measured is present or not [257].

decision threshold. A fixed value of the decision quantity by which, when exceeded by the result of an actual measurement of a measurand quantifying a physical effect, one decides that the physical effect is present [257].

(Note: The statistical test should be designed such that the probability of wrongly rejecting the hypothesis (error of the first kind) is equal to a given value α. For this standard, $\alpha = 5\%$.)

detector. A material or device that is sensitive to radiation and can produce a response signal suitable for measurement or analysis; a radiation detection instrument.

scintillation detector. A detector consisting of a scintillator that is usually optically coupled to a photosensitive device, either directly or through light guides (modified from Ref. [257]).

(Note: Both solid state scintillators (e.g. NaI(Tl), CsI(Tl), CsI(Na), CsI(pure), CsF, KI(Tl), LiI(Eu), $LaCl_3$(Ce), $LaBr_3$(Ce) and BGO) and liquid scintillators are used.)

high purity germanium detector (HPGe detector). A semiconductor detector that relies on production of free electrons and holes in a high purity germanium crystal.

sodium iodide detector (NaI(Tl) detector). A scintillation detector that is based on the cristal of sodium iodide doped with thallium.

solid state nuclear track detector (SSNTD). A solid material (photographic emulsion, crystal, glass or plastic) that, after having been exposed to ionizing radiation, keeps the nano-scale damages (nuclear tracks) caused by the radiation.

(Note: The SSNTD should be etched and examined microscopically. The tracks of nuclear particles are etched faster than the bulk material, and the size and shape of these tracks yield information

about the mass, charge, energy and direction of motion of the particles. Also known as an etched track detector or a dielectric track detector, DTD.)

detection limit. A smallest true value of the measurand which is detectable by the measuring method [257].
(Note: The detection limit is the smallest true value of the measurand which is associated with the statistical test and hypotheses (see 'decision quantity') by the following characteristics: if in reality the true value is equal to or exceeds the detection limit, the probability of wrongly not rejecting the hypothesis (error of the second kind) shall be at most equal to a given value β. For this standard, β = 5%.)

direct radiation. The direct emission of radiation from the source, which causes the external exposure of members of the public.

dispersion. The spreading of radionuclides in air (aerodynamic dispersion) or water (hydrodynamic dispersion) resulting mainly from physical processes affecting the velocity of different molecules in the medium.
(Note: Often used in a more general sense combining all processes (including molecular diffusion) that result in the spreading of a plume. The terms atmospheric dispersion and hydrodynamic dispersion are used in this more general sense for plumes in air and water, respectively. In normal language synonymous with dispersal, but dispersion is mostly used more specifically as defined above, whereas dispersal is typically (though not universally) used as a more general expression.)

distribution coefficient. The quantity of the radionuclide sorbed by a solid per unit weight of solid divided by the quantity of radionuclide dissolved in water per unit volume of water.

dose rate meter. A device that registers (and may record) the dose rate of ionizing radiation. Could be a component of the stationary or portable radiation detection instrument.

dosimeter. A portable instrument (such as a film badge or a thermoluminescent or electronic dosimeter) for measuring and recording the total accumulated dose of ionizing radiation. A radiation detection instrument.

electronic dosimeter. A digital electronic device that indicates directly the accumulated dose and, optionally, the dose rate of ionizing radiation.

thermoluminescent dosimeter (TLD). A device used to measure the radiation dose by measuring the amount of light emitted from a crystal in the detector when the crystal is heated after being exposed to the radiation.

film badge. Photographic film used for measurement of ionizing radiation exposure.

(Note: The film badge may contain two or three films of differing sensitivities, and it may also contain a filter that shields part of the film from certain types of radiation.)

dynamic range. The spread of radionuclide concentrations in a release (or the release rates) that can reliably be measured by an on-line monitoring system; the lower bound is determined by the detection limit and the upper bound by an unacceptably unreliable response of the system due to saturation of the detector pulse counting system.

environmental dose assessment model. A type of model specifically designed to address questions about radiation exposure of the public due to radioactive discharges to the environment.

gamma spectrometry. A measurement technique that separates the gamma rays emitted by the sample according to their energies, and allows the identification of emissions that are characteristic of particular radionuclides.

glass fibre filter paper. A high efficiency filter made of random glass fibres placed in an appropriate sample holder, which is used to trap particulate material.

gut transfer factor (fractional absorption in the gastrointestinal tract). The fraction of an ingested element that is directly absorbed to body fluids (from Ref. [242]).

(Note: Often referred to colloquially as gut transfer factor, 'f_1 or f_a value'. See also 'lung absorption type', a similar concept for the human respiratory tract.)

indicator organism. Biota that concentrate radionuclides effectively and can be used to assess trends in environmental radioactivity levels.

(Note: Such biota may not be important for human exposure.)

ionization chamber. A counter consisting of a chamber filled with a suitable gas, in which an electric field, insufficient to induce gas multiplication, is provided for the collection at the electrodes of charges associated with ions and the electrons produced in the sensitive volume of the detector by ionizing radiation. Modified from [Ref. 260].

isokinetic sampling. A condition that prevails when the velocity of air at the inlet plane of a nozzle is equal to the velocity of undisturbed air in a stack or duct at the point where the nozzle inlet is located.
(Note: Anisokinetic is the antonym of isokinetic. Subisokinetic refers to the condition where the nozzle inlet velocity is less than the free stream velocity. Super-isokinetic refers to the condition where the nozzle inlet velocity is greater than the free stream velocity (from Ref. [49]).)

minimum detectable activity (MDA). The radioactivity which, if present in a sample, produces a counting rate that will be detected (i.e. considered to be above background) with a certain level of confidence [1].
(Note: The 'certain level of confidence' is normally set at 95%, i.e. a sample containing exactly the minimum detectable activity will, as a result of random fluctuations, be taken to be free of radioactivity 5% of the time. The minimum detectable activity is sometimes referred to as the detection limit or lower limit of detection. The counting rate from a sample containing the minimum detectable activity is termed the determination level.)

minimum significant activity (MSA). The radioactivity which, if present in a sample, produces a counting rate that can be reliably distinguished from background with a certain level of confidence [1].
(Note: A sample containing exactly the minimum significant activity will, as a result of random fluctuations, be taken to be free of radioactivity 50% of the time, whereas a true background sample will be taken to be free of radioactivity 95% of the time. The minimum significant activity is sometimes referred to as the decision limit or decision threshold. The counting rate from a sample containing the minimum significant activity is termed the critical level.)

mixed oxide (MOX). A mixture of the oxides of uranium and plutonium used as reactor fuel for the recycling of plutonium in thermal nuclear reactors ('thermal recycling') and for fast reactors [260].

model. A mathematical abstraction of an ecological or biological system, including specific numerical values (or distributions of values) for the parameters of the system.

model validation. Documentation of the discrepancy or agreement between model predictions and actual events; typically, predicted concentration values for particular media are compared with accurately measured field data obtained over the range of conditions representing the extent of the intended application of the model.

monitoring. The measurement of dose or contamination for reasons related to the assessment or control of exposure to radiation or radioactive substances, and the interpretation of the results (from Ref. [1]).
(Note: The 'measurement' of dose often means the measurement of a dose equivalent quantity as a proxy (i.e. substitute) for a dose quantity that cannot be measured directly. Also, sampling may be involved as a preliminary step to measurement. 'Monitoring' may be subdivided in two different ways: for the purposes of this report: according to where the measurements are made, into individual monitoring, workplace monitoring, source monitoring and environmental monitoring; and, according to the purpose of the monitoring, into routine monitoring, task related monitoring and special monitoring.)

environmental monitoring. The measurement of external dose rates due to sources in the environment or of radionuclide concentrations in environmental media.

individual monitoring. Monitoring using measurements by equipment worn by individual workers, or measurements of quantities of radioactive material in or on their bodies.

source monitoring. The measurement of activity in radioactive material being released to the environment or of external dose rates due to sources within a facility or activity.

naturally occurring radioactive material (NORM). Radioactive material containing no significant amounts of radionuclides other than naturally occurring ones. The exact definition of 'significant amounts' would be a regulatory decision. Material in which the activity concentrations of the naturally occurring radionuclides have been changed by a process is included in naturally occurring radioactive material.

on-line monitoring system. A device, usually for airborne activity measurement, consisting of a sample extraction and delivery system, shielded counting chamber, radiation detector, associated electronics, with display and recorder or computerized data acquisition system, that measures continuously emissions from radionuclides flowing through the counting chamber or collected by sampling media located there.

operational quantities. Quantities used in practical applications for monitoring and investigating situations involving external exposure.
(Note: Operational quantities are defined for measurements and assessment of doses in the body. In internal dosimetry, no operational dose quantities have been defined which directly provide an assessment of equivalent or effective dose (from Ref. [30]).)

protection quantities. Dose quantities defined for the radiological protection purposes that allow quantification of the extent of exposure of the human body to ionizing radiation from both whole and partial body external irradiation and from intakes of radionuclides (modified from Ref. [30]).

radiation detection instrument. A device that detects and displays the characteristics of ionizing radiation.

reference material. Material or substance possessing one or more properties which are sufficiently well established to be used for calibration of an apparatus, assessment of a measuring method, or for assessing values to materials (ISO Guide 30).

reference person. An idealized person for whom the organ or tissue equivalent doses are calculated by averaging the corresponding doses of the ICRP 'reference male' and 'reference female'. The equivalent doses of the 'reference person' are used for calculation of the effective dose by multiplying these doses by the corresponding tissue weighting factors (from Ref. [30]).
(Note: The reference person is a fundamental concept, which underlies the protection quantity 'effective dose'. The effective dose is defined by the ICRP for the reference person exclusively. For assessments of the effective doses to members of the public, the ICRP uses six fixed ages of a reference person: newborn, 1, 5, 10 and 15 year olds, and an adult person.)

release. The act or process of releasing radioactive materials to the environment; also used to describe the material released (usually gaseous or liquid).

abnormal releases. Releases that occur as the result of an accident or other unusual condition within a nuclear facility.

airborne releases. Releases to the atmosphere of gases and aerosols.

liquid releases. Releases to the aquatic environment: rivers, lakes, sea or ocean.

discharge. Authorized release; also used to describe the activity of discharged material.

discharge rate. Activity of discharged material per unit time.

representative person. An individual receiving a dose that is representative of the more highly exposed individuals in the population (from Ref. [18]).
(Note: ICRP Publication 101 [18] also indicates that the dose to the representative person "... is the equivalent of, and replaces, the mean dose in the 'critical group' ", and provides guidance on assessing doses to the representative person. The assessments of doses to the representative person are based on the dose coefficients provided by the ICRP for the reference persons of different ages. The parameters which are required for estimating the distribution of effective doses to members of the public in space and time (such as consumption of foodstuffs, outdoor/indoor time budget, etc.) define the representative person.)

sample. Portion of materials selected from a large quantity of material (from Ref. [260]).

representative sample. A sample resulting from a sampling plan that can be expected to reflect adequately the properties of interest in the parent population (from Ref. [260]).

parent population. Totality of items under consideration (from Ref. [260]).

item. Each of discrete identifiable portions of material suitable for removal from a population as a sample or as a portion of a sample, and which can be individually considered, examined, tested or combined (from Ref. [260]).

sampling. Process of drawing a sample (from Ref. [260]).

air sampling. The collection of samples to detect the presence of, and/or to measure the quantity of volatile or solid radioactive material, non-radioactive particulate matter or various chemical pollutants in the air.

sampling device. Apparatus/tool to obtain a sample (from Ref. [260]).

sampling plan. Predetermined procedure for selection, withdrawal, preservation, transportation and preparation of the portions to be removed from a population as a sample (from Ref. [260]).

sampling procedure. Operational requirements and/or instructions relating to the use of a particular sampling plan (from Ref. [259]).

sampling technique. All appropriate procedures and sampling devices used to obtain and describe samples (adapted from Ref. [260]).

screening models. Simple models employing conservative assumptions for the expressed purpose of identifying radionuclides and exposure pathways of negligible importance to public exposures from a particular source in a particular environment.

site specific data. Information about important parameters used in assessment models that have been obtained for the particular location of interest for the assessment; if site specific data are unavailable, generic estimates (default values), based upon measurements at other locations, are employed.

spectrometry. Use of radiation detector and associated electronic systems to separate alpha, beta or gamma radiation with different energies from a sample and thus allow measurement of the different types of nuclides present.

survey meter. Any portable radiation detection instrument especially adapted for inspecting an area or individual to establish the existence and amount of radioactive material present.

transfer parameter (or **transfer coefficient).** The fraction of an element or radionuclide ingested daily by an animal that is: (a) secreted in milk; (b) present in meat; or (c) present in eggs at a steady state or equilibrium condition.

(Note: Transfer coefficients are typically given in units appropriate to the animal product. For example, the milk transfer coefficient is the ratio of radioactivity concentration in milk ($Bq \cdot L^{-1}$) to the daily intake ($Bq \cdot d^{-1}$), while the transfer coefficient to meat is the ratio of the concentration in edible flesh ($Bq \cdot kg^{-1}$) to the daily intake ($Bq \cdot d^{-1}$).)

trueness. The closeness of agreement between the average value obtained from a large series of test results and an accepted reference value. The measure of trueness is usually expressed in terms of bias.

ABBREVIATIONS

AMAD	activity median aerodynamic diameter
AMTD	activity median thermodynamic diameter
BSS	International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, see Ref. [2]
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
ICP-MS	inductively coupled mass spectrometry
IRSN	Institut de radioprotection et de sûreté nucléaire
ISO	International Organization for Standardization
IEC	International Electrotechnical Commission
FAO	Food and Agriculture Organization of the United Nations
GM	Geiger–Müller counter
HEPA filter	high efficiency particulate air filter
HPGe	high-purity germanium
HT	molecular tritium
HTO	tritiated water
LaBr	a scintillation detector
MCA	multichannel analyser
MDA	minimum detectable activity

MOX	mixed oxide
NaI/NaI(Tl)	a scintillation detector
NORM	naturally occurring radioactive material
NPP	nuclear power plant
NRPA	Norwegian Radiation Protection Authority
OBT	organically bound tritium
TLD	thermoluminescent dosimeter
SSNTD	solid state nuclear track detector
WBC	whole body counter
WHO	World Health Organization
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

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