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No. 72

Monitoring for Compliance with Remediation Criteria for Sites

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FOREWORD

Sites can become contaminated with radioactive material as a result of: authorized activities, operational incidents or accidents at one or more facilities located at a site; decommissioning activities; radiological accidents (such as at Chernobyl, Ukraine, or Goiânia, Brazil); or military activities (e.g. weapons tests). Such contaminated sites may require remediation.

In order to reduce the existing and potential radiation exposure from a contaminated site and to ensure the safety of workers, the public and the environment now and in the long term, remediation has to be planned and implemented in accordance with the radiological situation. After the completion of the remediation activities, final radiological monitoring of the remediated site is needed to demonstrate compliance with criteria for unrestricted or restricted use of the site.

Facilities and activities that may necessitate remediation are described in the publication Fundamental Safety Principles (IAEA Safety Standards Series No. SF-1). As described in that publication, the process of remediation itself can be considered to be an activity.

The IAEA has issued safety standards on remediation of sites contaminated by past activities and accidents (IAEA Safety Standards Series Nos WS-R-3 and WS-G-3.1), and on the development and implementation of criteria for release of sites (IAEA Safety Standards Series No. WS-G-5.1) at the end of an authorized practice. This Safety Report aims to provide detailed and practical advice in support of these safety standards on the development and implementation of a monitoring strategy to demonstrate compliance with criteria for release of contaminated sites for unrestricted or restricted use. The present Safety Report complements the Safety Report on Monitoring for Compliance with Exemption and Clearance Levels (Safety Reports Series No. 67), which focuses on clearance of bulk material from regulatory control.

The IAEA would like to express its appreciation to all of the experts who contributed to the development and review of this report. The IAEA officers responsible for this publication were B. Batandjieva and V. Ljubenov of the Division of Radiation, Transport and Waste Safety.

EDITORIAL NOTE

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Many uses of radioactive material in areas such as industry, research, cancer treatment and medical diagnosis are beneficial to humankind. However, radioactive material is also potentially harmful to health and the environment, and its use must, therefore, be regulated [1].

Activities, as defined in the Fundamental Safety Principles, can include remediation of sites affected by residues from past practices [2] as well as other sources of radiation that may cause radiation risks to humans. Remediation could be performed, for example, to remediate consequences from:

— Past activities, such as discontinued mining and milling operations [3];
— Accidents that cause spread of contaminated materials in environmental media [4];
— Weapons tests [5];
— Accidents leading to dispersal of airborne contamination [4];
— Inadequate management of radioactive material [6];
— Decommissioning of facilities;
— Past radioactive waste disposal practices [4].

Existing residual contamination must be identified, assessed and remediated where appropriate. Sites contaminated as a result of past activities or accidents vary widely in terms of:

— Type of contamination;
— Level of contamination;
— Type of area (urban, agricultural, industrial, etc.);
— Extent of contaminated areas (e.g. Semipalatinsk site, Chernobyl site and exclusion zone or part of a facility);
— Environmental media (e.g. soil, surface/underground water, air);
— Distribution of contamination in the affected areas (surface, depth, etc.).

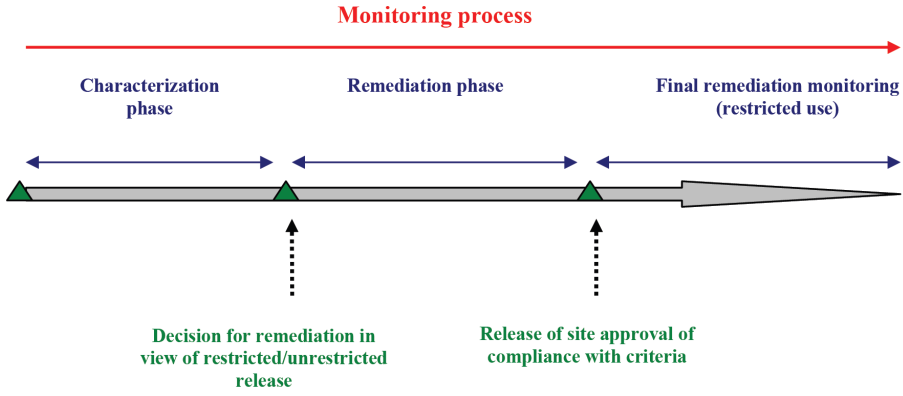

FIG. 1. Phases of remediation and monitoring activities to comply with release criteria.

Regardless of the situation resulting in contamination, monitoring[1] is necessary to:

— Determine the radiological conditions and whether there is residual contamination at the site[2];
— Determine the qualitative and quantitative characteristics of residual activity;
— Determine whether the activity at the site is below the established criteria;
— Identify whether there are areas with elevated activity;
— Support or identify the need for further remediation;
— Justify release of the site from regulatory control (on radiological grounds).

This publication focuses on final remediation monitoring, although in a remediation project, monitoring needs to be conducted throughout the remediation process (Fig. 1), and covers:

— Monitoring prior to remediation of a contaminated site to help define the need for and extent of remediation in order to ensure compliance with safety requirements and criteria, including those on remediation and release

[1] The term 'monitoring', as used in this publication, means "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" [7].

[2] The term 'site', as used in this publication, means land together with any buildings or other structures being considered for release from regulatory control [8].

of a site from regulatory control. During this phase, monitoring is necessary in order to define the level and boundaries of contamination; types of contaminated media (soil, subsurface water, groundwater, flora, fauna, etc. (Figs 2 and 3)); homogeneity and elevated levels. The necessary remediation activities will be defined based on the collected historical information and data obtained from the site characterization, remediation criteria and other sources of information. Monitoring needs to be conducted with instruments and analyses that have adequate detection capabilities to demonstrate compliance with the established concentrations of the relevant isotopes (see Section 3).

The term 'characterization', as used in this publication, refers to the step in the decommissioning or remediation planning process in which information is gathered to support the development of the remediation planning process, help identify health and safety issues, estimate waste types and volumes, and develop a valid cost estimate.

— Monitoring during remediation is necessary to ensure that protection of workers is adequate and in compliance with safety requirements and criteria. Monitoring is also necessary to detect any deviations from the expected level of contamination or elevated radioactivity at the site. In this and previous phases, all monitoring data need to be recorded, analysed and, if necessary, further monitoring or remedial measures are to be defined. Monitoring at this phase can also be used to facilitate the next stage of post-remediation monitoring.

FIG. 2. Characterization of contaminated sites (Chernobyl nuclear power plant exclusion zone, Ukraine).

FIG. 3. Chernobyl nuclear power plant (Ukraine).

— Final remediation monitoring (also referred to as post-remediation monitoring) includes monitoring after completion of remediation, as well as any subsequent monitoring and surveillance after a decision has been made by the regulatory body for release of the site for restricted use. Final remediation monitoring ensures that the site has been adequately remediated and can be released for unrestricted or restricted use, or that the site requires further actions.

  In the event that the site is eventually released for restricted use, there may be a need for additional confirmatory monitoring over a longer timescale to confirm that the site status remains acceptable.

  Final remediation monitoring for compliance after completion of remediation must be carried out based on a strategy with the following objectives:

  • To demonstrate that the site is adequately and sufficiently well characterized in terms of the nature, quantity and distribution of the residual radioactivity;
  • To demonstrate that residual contamination at the site (or part of the site) is below the established criteria for site release for unrestricted use and will not have deleterious effects on the public and the environment.

If compliance with the site remediation or release criteria cannot be confirmed [8], appropriate further actions need to be defined (e.g. further monitoring, institutional controls, further remediation actions).

Such monitoring for compliance with remediation criteria follows several main stages as presented in Table 1.

TABLE 1. MAIN STAGES OF FINAL REMEDIATION MONITORING FOR COMPLIANCE

Stages	Specific activities
Planning (see Section 3)	Specification of the site
	Confirmation of radiological criteria to be complied with
	Confirmation of radionuclides of concern and derivation of practical criteria to be applied during monitoring
	Options for monitoring and selection of instrumentation
	Confirmation of the required level of confidence
	Cost assessment for the monitoring effort
	Selection of a management approach for monitoring
	Selection of the optimum monitoring strategy
Implementation (see Section 4)	Application of the monitoring strategy
	Use of instrumentation
	Conducting/performing monitoring
Assessment (see Section 5)	Data review, validation and verification
	Review of precision, completeness and representativeness
	Assessment of monitoring results (statistical tests and evaluation measurement comparison)
Decision making (see Section 6)	Decision for compliance with criteria for the survey units[a]
	Compliance of the entire site
	Specification of follow-up actions
Formal reporting (see Section 7)	Documentation of strategy implementation and results
	Reporting to regulatory body
	Reporting to other interested parties

[a] A 'survey unit', as defined in this publication, is a geographical area consisting of structures or land areas of specified size and shape at a remediated site for which a separate decision will be made as to whether the unit attains the site specific reference remediation criteria. Survey units are generally formed by grouping contiguous site areas with a similar use history and the same classification of contamination potential. Survey units are established to facilitate the survey process and the statistical analysis of survey data [9].

The decision on compliance of a site (or part of a site) with the relevant safety criteria depends on several factors, including:

— The remediation process;
— Potential future use of the site (i.e. the defined end state);

— Criteria applied during remediation;
— Level of confidence in meeting the safety criteria.

The regulatory body is expected to make a decision on demonstration of compliance with criteria for a site, based on its evaluation of the sufficiency, adequacy and accuracy of the monitoring approach, and results that are documented and presented by the operator and which demonstrate that the results comply with the relevant release criteria. It is prudent to have the regulatory body give its approval or tacit approval of the plan and then final approval when the results are known.

1.2. OBJECTIVE

The objective of this Safety Report is to provide practical advice on the development and implementation of strategies for monitoring for compliance with remediation criteria [10] after completion of remediation activities, consistent with contemporary radiation protection principles and experience gained in remediation, decommissioning and release of sites from regulatory control. This publication is intended to provide practical information on how to demonstrate compliance with remediation or release criteria for land (primarily soil and other associated media), which affect the regulatory decision for release of that site from regulatory control. This Safety Report is, therefore, intended to complement the safety requirements and guides for remediation [10, 11]. It could also be useful for release of sites from authorized activities [8].

This Safety Report covers sites which are contaminated by past activities or accidents. It is addressed to those responsible for the development, implementation and review of monitoring activities for compliance with release criteria after remediation is complete. The term ‘operator’, as used in this publication, refers to the organization that has the responsibility to plan and implement the monitoring and for general safety at the site.

This Safety Report also has the objective of assisting the regulatory body or other independent organizations to review and verify whether:

— An optimum remediation strategy has been selected and applied;
— Representative analysis and results have been obtained by the operators to justify and provide a sufficient level of confidence for compliance with established remediation criteria [10] and release criteria [8] as identified in the remediation plan.

1.3. SCOPE

This Safety Report addresses monitoring for compliance with remediation at the final stage of the remediation process related to interventions, meaning sites contaminated by past activities and accidents. However, the methodology applied in this Safety Report may also be used for licence termination processes with appropriate consideration of relevant criteria for site release [8]. The sites considered in this Safety Report include:

— Sites affected by radiological accidents;
— Sites with inadequate management of radioactive material or inadequate past radioactive waste management practices;
— Sites where natural or artificially-generated radionuclides were used, deposited or treated (e.g. medical, radiopharmaceutical, research, educational, dispersal and others);
— Facilities that operated at some time without a licence from a regulatory body.

This Safety Report applies to monitoring of sites that include land, buildings, and structures above or under the ground. Other media that may pose potential exposure pathways are also considered, including subsurface soil, surface and groundwater, underground objects or structures that remain at the site, flora and fauna located on the contaminated site, and potentially affected areas around the site.

This Safety Report does not address the monitoring of bulk material, waste disposal sites, and mining and mill sites since they are addressed in other publications [2, 12, 13]. It also does not directly cover monitoring during the characterization phase and implementation of remediation activities (see Fig. 1). However, the monitoring principles presented here are also broadly valid for these phases. Indeed, the conduct of monitoring during the remediation operations can help to facilitate the effectiveness of the final remediation monitoring. Hence, the planning of the final monitoring stage needs to be integrated, to the extent possible, with the planning and implementation of the monitoring prior to and during remediation (Fig. 1).

The present publication focuses on the key factors in the:

— Planning and selection of a monitoring strategy (e.g. monitoring equipment and techniques);
— Implementation of the monitoring activities to obtain representative results and the required level of confidence for demonstration of compliance with release criteria;

FIG. 4. Rocky Flats site (United States of America).

— Assessment of the results;
— Decision making process on compliance of the site with established criteria for unrestricted or restricted use;
— Formal reporting of results (see Table 1).

Two examples of sites in Member States where remediation is occurring are shown in Figs 3 and 4.

Some sites may be contaminated both radiologically and chemically, and the possibility of release of the site will depend on the level of both types of residual contamination. Although the present Safety Report does not deal with non-radiological contamination, it recognizes the importance of considering the associated non-radiological hazards together with radiological hazards in the development and implementation of final remediation monitoring.

1.4. STRUCTURE

Following this introduction, an overview of the development of the final remediation monitoring strategy, in the context of the overall remediation process, is described in Section 2. The monitoring planning, preparation and selection of a monitoring strategy are described in Section 3. Section 4 discusses the key considerations related to the implementation of final remediation monitoring. Analysis and interpretation of results are addressed in Section 5. Important considerations in the decision process for compliance with safety criteria are presented in Section 6. Section 7 discusses the requirement for the formal reporting of the results from the final remediation monitoring. Section 8 addresses the aspects of verification surveys. Detailed supporting material and examples are included as appendices to this Safety Report.

2. DEVELOPMENT OF A STRATEGY FOR FINAL MONITORING FOLLOWING REMEDIATION

The development of the strategy for final remediation monitoring must take place in the context of the overall remediation process. The major steps in the development of the monitoring strategy are presented in Fig. 5.

The goals of the remediation are based on dose constraints, typically described in annual dose levels, which then correspond to reference levels, generic or special. The reference levels are expressed as remediation criteria or site release criteria, usually in becquerels per gram. To effectively implement remediation goals in field activities, remediation criteria must be converted to units that are measured by field instruments and, in this publication, are described as derived remediation criteria. Field monitoring is typically performed to check remediation activities until the derived remediation criteria indicate that the remaining contamination achieves the remediation goal. In other words, monitoring the remediation process requires that the dose be expressed in terms of field instrument readings.

The early stages of the remediation process include site definition, assessment of historical data, specification of remediation and site release criteria, and the scoping survey. They all support the development of the remediation plan which defines the overall approach to the remediation task. The remediation activity requires a supporting monitoring programme aimed at the protection of workers, the public and the environment, and tracking the progress of remediation. This monitoring can also contribute to the effectiveness of the final remediation monitoring programme, for example, by demonstrating that excavated areas are below the established safety criteria prior to backfill. However, to be effective and meet the objectives, the instruments and techniques used after remediation is completed must meet the specifications for the derived remediation criteria.

This process of final remediation monitoring involves five main stages as presented in Fig. 5 and Table 1:

— Planning;
— Implementation;
— Assessment of results;
— Decision on compliance;
— Formal reporting of results.

These stages are discussed in the following sections of this Safety Report.

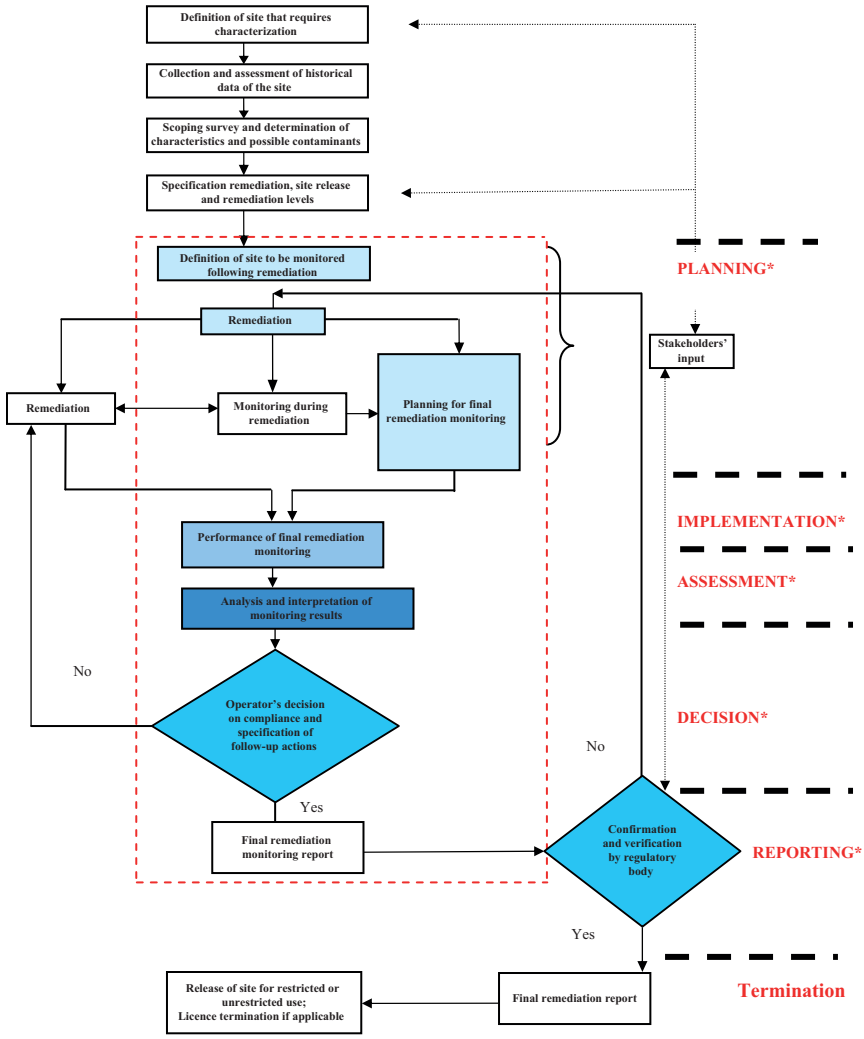

FIG. 5. Schematic presentation of the monitoring process for compliance (the asterisks indicate final remediation monitoring).

Following the reporting of results, including the operator's recommendations regarding the release of the site from regulatory control, the regulatory body needs to decide on the compliance of the site with relevant safety requirements and criteria. The options are: (i) unrestricted use; (ii) restricted use, including the definition of the restrictions; or (iii) the need for further remediation. Once all necessary remediation has been completed to the satisfaction of the regulatory body, the operator completes a final remediation report — this report is not covered by this publication.

The approach illustrated in Fig. 5 provides for the involvement of appropriate interested parties during monitoring at different stages of the remediation process as related to the strategy and implementation of the programme for final remediation monitoring. This is discussed in more detail in Ref. [11].

2.1. CONSIDERATIONS IN THE DEVELOPMENT OF THE FINAL MONITORING STRATEGY

It is possible that the regulatory body will be prescriptive in defining the monitoring approach for demonstration of compliance with the remediation criteria. These guidelines will be based on safety criteria established by the regulatory body and related to the potential exposure of the public to residual contamination in environmental media (e.g. soil, water). Typically, the criteria and reference values will address the unrestricted or restricted use of sites after remediation [6].

Unrestricted use of sites denotes that the level of residual contamination is low enough in the various environmental media that further remediation, and usually further monitoring, is not required by the operator or by the regulatory body. The site may be used for any purpose by any future owner. This is usually demonstrated by estimates of the most conservative reuse of the land following release. For example, a conservative reuse may be a resident farmer. The scenario would specify the exposure pathways to be considered and the corresponding parameters, such as the number of hours the farmer and his family would be on the premises each year, what crops and farm animals would be raised for food, and how much water would be used annually and how. This type of scenario typically provides a conservative estimate of doses to the members of the critical group.

The monitoring strategy would include sampling and measurements for the radionuclides in question to ensure that the criteria were met. This could involve techniques that include scanning and static measurements with radiological detection instruments. The techniques that are used are usually documented in

formal procedures. A quality assurance (QA) programme needs to be in place to provide audits to ensure that the procedures are followed. It needs to be noted that the final remediation monitoring for release for unrestricted use may require significant resources to convince the regulatory body and other interested parties that the site is in compliance with the established safety criteria.

Release of a site for restricted use normally includes additional requirements for the operator and future owners of the site. Restricted use may be appropriate for sites that are so extensively contaminated to the point that it is impractical to remediate the entire site to levels required for release for unrestricted use from an economic point of view. Release for restricted use includes restrictions or controls; for example, the site can only be used for an industrial facility as opposed to a resident farmer. The final remediation monitoring for restricted release may not require the resources that are necessary for release for unrestricted use of a site.

2.2. APPROACH FOR DETERMINING A STRATEGY FOR FINAL REMEDIATION MONITORING

Although release for unrestricted use of a site is the desired goal of remediation, based on the situation at the site (e.g. level of contamination) it may be necessary to achieve only restricted release criteria. Early recognition of the expected final status of the site allows the efficient use of financial and human resources. An important step in the determination of the final status of the site is the determination of interested parties and solicitation of their input. The consensus goal of the remediation may be release of the site for unrestricted use. However, during the remediation process, it may become apparent that this is not a practical alternative. The interested parties would need to participate in determining the path forward. In the case that the remediation goal is to be modified, it will need the approval of the regulatory body.

The strategy for final remediation monitoring depends on the goal of the remediation effort (end state). Models are used to develop site specific release criteria for the relevant radionuclides. These criteria define the required detection capabilities of the equipment to be used in the final remediation monitoring. The detection capabilities limit the choice of instruments that can be used. The instruments that will be used to allow for the measurement of the derived criteria are determined, along with monitoring processes that ensure that the instruments will be used in an adequate manner to achieve the monitoring goals. Statistical interpretation of the monitoring results is used to confirm that the criteria have been met.

For the final remediation monitoring to be performed satisfactorily, the appropriate guidance (i.e. procedures, records and reports, etc.) needs to be included in the original remediation plan and the operator's method statements. The regulatory body typically reviews the remediation plan and, often, data that will be included in the final remediation monitoring report. This information includes all of the measurements or sample analyses collected during final remediation monitoring. The regulatory body reviews the information carefully and decides whether it provides compelling evidence that the remediation criteria have been met. They may provide informal feedback to the operator during remediation and during the conduct of the final remediation monitoring. Information about the final remediation monitoring can also be provided to other interested parties.

The application of the monitoring strategy is illustrated in a practical example presented in Appendix I.

3. PLANNING

3.1. PLANNING OVERVIEW

The final remediation monitoring process for demonstration of compliance with remediation or site release criteria is more complicated and time consuming than routine radiation monitoring of facilities using radioactive material. This is because accurate measurements of low levels of radioactivity and large quantities of data are often needed to provide the basis for a technically defensible decision for compliance with established criteria.

The effectiveness of final remediation monitoring for compliance with remediation criteria depends on:

— An understanding of the site;
— Knowledge of the desired end state and radiological criteria;
— Development of the end state (unrestricted or restricted use);
— Understanding of the uncertainties associated with the decision for demonstrating compliance;
— Choice of the correct monitoring techniques and equipment;
— Appropriate procedures to make measurements to the required standard;
— Regular review of the information generated during final remediation monitoring;

— Measures for responding to unexpected elevated levels or problems with equipment;
— Having an effective quality management system;
— Documentation of the monitoring approach and results which give confidence in the findings and conclusions.

If the remediation work is performed as planned, the fundamental information needs to be contained in the remediation plan on which monitoring for compliance will be based (see Fig. 5).

The remediation plan provides the basic information to develop the monitoring process for final remediation confirmation and the basis for compliance of a remediated site. This information needs to be reviewed carefully as it establishes the basis for planning the monitoring for compliance, with a view to convincing other interested parties that the radiological end state is met with or without restrictions in place. Failure to understand the site and the end state of remediation at this point will invalidate subsequent work. If the remediation plan has, in any way, failed to identify significant information, then the remediation plan will need to be reviewed to decide whether this could have compromised the achievement of the stated goal and compliance with remediation criteria.

The final remediation monitoring strategy and plan will include the results of the monitoring performed during remediation activities. These results will need to give confidence that the remediation was completed with a good understanding of the site, remediation and site release criteria. The strategy for the final remediation monitoring plan also needs to:

— Ideally, demonstrate that the operator has used all relevant historical data to develop an initial idea of the likely radionuclides expected.
— Show understanding of the natural background levels and also levels of any artificial or concentrations of naturally occurring radionuclides which are not required to be remediated. This can include, for example, fallout from weapons tests conducted in the 1950s and 1960s. Background levels can also vary significantly with geology and with construction material present at the site.
— Demonstrate that the predicted radionuclide vector was confirmed or modified by preliminary measurement, generally involving sampling and radiochemistry (a radionuclide vector is a set of radionuclides and their relative concentrations which have been found to be approximately constant over a defined area, some of which are difficult to measure directly or by analysis).

— Demonstrate that the radionuclide vector (see Section 3.3) has been regularly reviewed as the remediation activities progressed, taking account of the different chemical and physical forms of the contaminant and the changing geology, chemistry and groundwater flow of the site. It must also be shown that differences between the initial expectation of the radionuclide vector and the best estimate used during the evaluation of the data are understood and can be explained in a credible way.

Experience shows that it is unwise to leave planning of the final remediation monitoring to the end of the remediation effort. Review and confirmation of the plan for final remediation monitoring need to be performed before and in parallel with remediation activities (see Fig. 5). In this way, unexpected changes in site conditions can be identified as they occur and expensive reworking of the strategy for final remediation monitoring is avoided. This may mean that more remediation work is required than anticipated but can avoid additional monitoring effort, thus resulting in significant cost and time savings.

3.2. RADIOLOGICAL CRITERIA

The purpose of the remediation process is to remediate an area below established remediation or site release criteria. These criteria will be established by the regulatory body or be proposed by the operator of a specific site in accordance with national safety requirements (dose levels/limits and constraints) and then be approved by the regulatory body [14]. These criteria need to be based on principles of radiation protection following a systematic approach for evaluation of safety during and after remediation, and need to be included and considered in the development and implementation of the remediation plan.

For sites contaminated by past activities, the IAEA has recommended reference levels in terms of dose equivalent in a year [10, 11] above which remediation activities need to be considered.

If the area meets the required site release criteria [8], the area may be released without restrictions. In this situation, the prevailing conditions are considered to be the residual background conditions for a new activity or for use of the land for habitation [8] (see Figs 5 and 6).

It must be mentioned, however, that national regulation may define other release criteria.

For the purpose of the final remediation monitoring for compliance with the site specific criteria, it is important to convert these criteria into measurable units corresponding to the selected instruments to be used during the final remediation

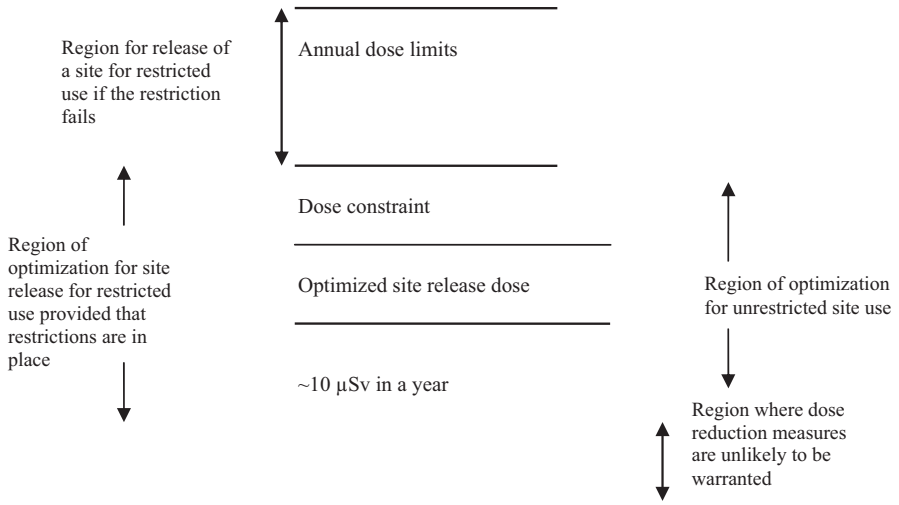

FIG. 6. Constrained optimization and regions of effective dose for members of the critical group in the release of sites [8].

monitoring since annual effective dose to the member of a critical group is not a measurable quantity. Therefore, the site specific remediation or site release criteria need to be derived and expressed in terms of measurable quantities, such as dose rate to air (kerma), instrument response (cpm), radionuclide specific activity concentration (e.g. Bq/g or Bq/kg) for sample analysis, surface activity levels (e.g. Bq/cm^2 or Bq/m^2) or total activity (Bq). This determination of derived remediation criteria is typically determined at the beginning of the remediation process and is used until the final decision on compliance with criteria is made. The derivation of these criteria requires knowledge of the contamination, instrument characteristics, relevant exposure pathways and monitoring processes (use of instruments, i.e. ratemeter mode or scalar mode).

The derived remediation criteria are radionuclide specific. However, it must be borne in mind that sites can be contaminated by more than one radionuclide and, in this case, the unity rule is applicable as presented in Appendix II.

3.3. CONTAMINANTS

The monitoring strategy after remediation strongly depends on a clear knowledge of the contaminants which were present at the site before and those that remain following remediation. Therefore, identification and evaluation of the available site specific historical data (e.g. historical records, knowledge of the

types of processes that caused contamination, experience gained elsewhere, public or professional memory) and characterization data prior to and during the remediation are essential for defining the strategy for monitoring for compliance with release criteria.

The remediation plan includes this information about the site but it is important that this information be reviewed carefully, confirmed and not taken at face value in developing the final remediation monitoring plan. If attention is not paid to this aspect, the monitoring process runs the risk of making the same mistakes and perhaps missing a radiologically significant contaminant or contaminants. To obtain a good understanding of the type and estimated level of contamination at the site following remediation, it is important in the planning of the final remediation monitoring to:

— Review and take into consideration the available historical information of the site. As part of the remediation plan, there needs to be a comprehensive description of the activities that took place at the site which caused contamination or the possibility of contamination. This information can be based on many sources as presented in Appendix III.
— Consider whether the potential contaminants from the operation occur in the background at the facility. Different statistical tests for evaluation of monitoring data may be necessary if the contaminants occur in the background, especially if the derived remediation criteria are not significantly above background concentrations [15]. For additional information on this topic, please see the Bibliography and Appendix IX.
— Review the logic of identifying the radionuclides likely to be present and the methods which were employed to detect and confirm their presence prior to and during remediation, and to confirm that no radionuclides which could be present as radiologically significant radionuclide vector components could have been missed. As an example, tritium is extremely mobile and will spread much further and faster than other contaminants. Hence, it may be found at some distances, up to kilometres, from the point of leakage or discharge.
— Compare gross analysis results (alpha and beta) to the sum of the specific radionuclide analyses. If, for example, the gross alpha concentration of a sample that only has Pu isotopes is 30 Bq/g but the sum of the Pu alpha isotopes from a specific Pu analysis of that sample totals 10 Bq/g, there may be other alpha emitting radionuclides in the sample that were not expected. One or more radionuclide vectors at the end of the remediation process, as defined in the remediation plan, should be reviewed and confirmed. The relative concentration of the constituents in a radionuclide vector can change as a function of space and time. A classic problem is with tritium,

which is extremely mobile and is often found far from its point of release. Problems can also be found with changes in the ^{241}Am:^{239}Pu and ^{137}Cs:^{90}Sr + ^{90}Y ratios, and even with the ^{90}Sr:^{90}Y ratio due to differences in the chemical and physical properties of the media.

The concept of a radionuclide vector is important as many radionuclides cannot be monitored easily and require costly and time consuming radiochemistry to analyse specifically. However, in many cases, these difficult radionuclides will be found at a relatively fixed concentration ratio to other, easier to detect, radionuclides. The remediation process can then proceed based on the measurement of the easily detected radionuclides. The concentration of these radionuclides is then reduced until the radiological end state criterion is reached.

In some situations, part of the site may have a higher level of residual activity. Therefore, the operator needs to be aware of the boundaries of such areas and the acceptable levels both within and outside these areas with elevated levels. Such situations exist at several former nuclear sites and the methods adopted at these sites have been to use very sensitive scanning methods to cover 100% of the ground (see also Section 3.10).

3.4. DECISION ABOUT A RADIONUCLIDE VECTOR

After completion of the remediation activities and review of the remediation plan, the operator needs to determine the radionuclide vector on which the final remediation monitoring plan will be based. The radionuclide vector may be based on calculation, for example, as a product of a programme such as Origen [16]. It is desirable that this initial estimate be justified early on by full sample analysis of the potential contaminants during the characterization and at the start of the remediation activities. Once the site has been remediated to a high standard, it may be difficult to find a sample with measurable activity to allow credible analysis of all of the potential contaminants. In that case, monitoring has to proceed on the basis of the remediation radionuclide vector. Where sampling and analysis are possible, it is essential that the operator use this information to confirm that the radionuclide vector during remediation is still valid. A good rule is to screen samples when they are collected. Those with a higher activity are candidates for a more complete radioanalytical assay so that the radionuclide vector can be confirmed.

There are many sites where the radionuclide vector will change with depth, perhaps as a consequence of different solubility and diffusion rates, but perhaps also because the surface deposition of radionuclides varied over time (see Figs 7

and 8). In such a case, the remediation end state of the more highly contaminated areas may well be set on the radionuclides which are expected to remain after remediation. Another typical example is contamination by mixed fission products. Over time, the ^{90}Sr component may dissociate from the ^{137}Cs contamination. If the remediation end state is based on the easily measured ^{137}Cs but the ^{90}Sr has dissociated, then there is the possibility that one area may be overly remediated for ^{137}Cs. However, if the ^{90}Sr has dissociated, the ^{137}Cs concentration may be lower relative to the ^{90}Sr concentration, so that that area may not be adequately remediated.

Factors which can affect the stability of a radionuclide vector include the relative mobility of the chemical species involved, which is dependent on the local geology and groundwater flow. For example, as an area is remediated, the more active areas are removed. As the remediation activities move from more contaminated areas to less contaminated areas, the radionuclide vector will change and the relative concentration of the more mobile radionuclides increases. The operator needs to check on the radionuclide vector stability when planning the final remediation monitoring.

FIG. 7. Example of an old waste processing facility that had experienced numerous leaks and spills prior to the start of decommissioning. The expected radioactive element is plutonium [17].

FIG. 8. Extent of subsurface contamination of numerous radionuclides with much higher mobility than plutonium that were discovered during remediation of a land area under the old waste processing facility [17].

3.5. AVERAGING AREA/SURVEY UNITS

In order to develop and implement the strategy for final remediation monitoring, it is necessary to define the size of the site, taking into account the information available at the characterization and remediation stages. The site is usually divided into discrete individual areas referred to as survey units. Decisions on compliance with remediation criteria and release are made separately for each of the survey units. They are defined to ensure a relatively uniform distribution of sampling/measurement locations among areas of similar contamination potential, history and other characteristics. There may be an area which is unique or has particular characteristics that distinguish it from the balance of the site that would usually be considered a separate survey unit. This division into specific defined areas supports the graded approach concept and facilitates the design, implementation and evaluation by limiting monitored areas and quantities of data into smaller, more easily managed groupings of monitoring activities.

A survey unit is a contiguous area, comprised of land of the same contamination potential classification. Survey units, limited in size by definition, need to be based on the:

— Contamination potential classification;
— Parameters used in pathway modelling to establish derived remediation criteria;
— Site specific conditions.

A survey unit is distinct from the averaging area. A survey unit is used to determine, on an area by area basis, whether the remediation criteria have been met. A remediated site may have a number of survey units that pass, and one or more that do not pass and require subsequent management. The averaging area is the amount of surface that a sample needs to statistically represent. In some cases where individual samples exceed the remediation criteria, if the area that the elevated measurement represents is small, the survey unit may still pass the evaluation. However, if the area over which the elevated measurement is large, the survey unit will fail, even though the median concentration may lead one to think that the unit has passed. For a more detailed review of application of averaging areas for elevated measurement, see Refs [9, 12]. The averaging area is determined by an evaluation of various elements, including:

— The anticipated future use of the site: For example, in an area which is already in use for housing, the averaging area needs to be a small fraction of a hectare and needs to lead to several measurements for even the smallest housing plot. In other cases, where there is no reason to suppose that a person would spend a major fraction of their time in a small area, the averaging area could be larger. This decision is particularly important when dealing with measurements involving sampling where it is extremely expensive to produce highly detailed data.
— Contaminant(s): For areas where the major contaminant is a gamma emitter, then the problem is much less severe as detailed measurements are relatively inexpensive.
— Contamination mechanism: The contamination mechanism has a bearing on the development of survey areas. Relatively large averaging areas are acceptable where the contamination originated from fallout from a stack, for example. In such a case, the rate of change of ground contamination with distance is minor. However, if the potential contamination is buried waste in pits, then a large averaging area is inappropriate, since significant changes in contamination type and concentration can vary over small distances.
— Activity concentration level: The activity concentration in becquerels per gram varies with the permissible averaging area and depth. This is particularly important if the contaminant is present in low concentrations on the surface and is not expected to be remediated. A greater depth of sample,

for example, 15 cm depth compared to 5 cm depth, could result in a lower average concentration.
— A surface activity in becquerels per square centimetre for identified objects or materials, together with a defined averaging area: This is particularly relevant for drains.
— A limiting air kerma rate (equivalent to a dose rate to air or an exposure rate).
— An activity in air limit: This is particularly important when dealing with radon emanation from radium sites.

Survey units can vary in terms of size, depending on various factors such as hazard potential (as presented in Table 2). Land areas less than approximately 100 m^2 need not be grouped into survey units. Rather, a few measurements/samples need to be obtained, based on professional judgement, to be representative of the highest contamination levels in the area and these values compared directly to the derived remediation criteria for determining compliance. Larger survey unit areas need to be justified and the justification documented. Each survey unit is monitored and the data are independently evaluated and compared with the derived remediation criteria. The average area/survey unit is normally derived from guidance similar to that stated in Table 2.

3.6. OPTIONS FOR MONITORING TECHNIQUES

Various monitoring techniques can be considered in planning the final remediation monitoring. These techniques are summarized below and elaborated in more detail in Section 4.3:

— In situ measurement prior to excavation;
— Measurement immediately after excavation;

TABLE 2. SURVEY UNIT AREAS [18]

Hazard (contamination) potential	Suggested maximum area for a land area survey unit (m^2)	Suggested maximum area for building surface survey unit (m^2)
Low	No limit	No limit
Medium	$<10^4$	100–1000
High	<2000	<100

— Measurement in bulk but elsewhere [12];
— Measurement by sampling and on-site processing;
— Measurement by sampling, followed by off-site processing.

On most sites, a combination of these techniques will be employed. The operator needs to very clearly demonstrate the logic of the choice for the selected techniques in specific cases, and show that the equipment and services will allow them to demonstrate compliance with the remediation or site release criteria (see Section 3.2). Areas which fail to meet the criteria are documented as discussed in Section 7.

3.7. INSTRUMENTATION

Once the monitoring techniques have been selected, the operator needs to select suitable equipment (see Appendix IV). In developing a strategy for final remediation monitoring, two main tasks need to be performed by the operator with respect to the monitoring instrumentation:

(a) Checking that the instrumentation used in the characterization and remediation stages was appropriately used and calibrated, with correct maximum tolerable indications and appropriate methods of use. These aspects are discussed in more detail below and summarized in Section 4.
(b) Choosing and calibrating instruments for the final remediation monitoring activities.

One obvious economy and advantage is to use the same types of instrument, or perhaps even the same instruments, used during the characterization and remediation of the site, but this may not be possible due to the difference in safety criteria for remediation and site release. It is important that the operator carefully review the choice of equipment and has confidence that the instruments are not working at the limits of their capabilities at the low levels usually expected during the final remediation monitoring. Generally, it is desirable that the operator should be able to make credible measurements for approximately 20–30% of the derived criteria. This is not always possible and it may be necessary to adopt a statistical process to evaluate the results (for more details, see Section 4.2).

The operator needs to explain the choice of specific instrument types. This can involve information about the procedure followed for selection of equipment. An example is provided in Fig. 9.

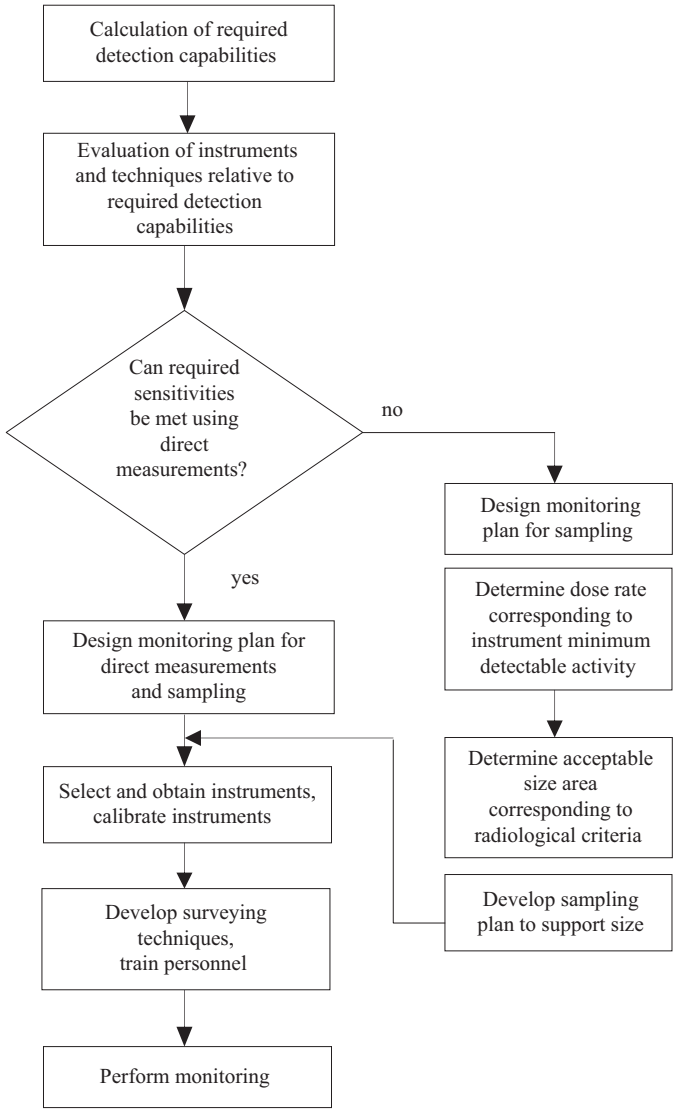

FIG. 9. Main steps of selection of instrumentation (adapted from MARSSIM [9]).

There are several key features of the selection process:

— Can the instrument be set up in a way to measure the quantity of interest? Sometimes this may be obvious, for example, the measurement of air kerma rate or radon concentration, but other times, such as the measurement of biota, instrument choice is less obvious.

— Does the instrument respond to the radionuclide vector effectively? This does not mean it has to respond to every radionuclide in the radionuclide vector, only that it responds to the major component (key radionuclide) which is likely to be stable and resistant to changes in measurement conditions. For example, where there is potential for surface contamination from a mixture of high and low energy beta emitters, it is generally worthwhile to select an instrument which only responds to the higher energy betas. It can have a thicker and, hence, more robust window, and thin layers of grease and grime will not influence the measurement.

3.8. UNCERTAINTY AND LEVEL OF CONFIDENCE

In a remediation project, radiological conditions change, sometimes in an unexpected way. This presents a challenge for final remediation monitoring. This is particularly important for large projects which require regular review of the monitoring strategy, monitoring results and compliance with derived remediation criteria. Final remediation monitoring aims to demonstrate confidence in the operator, regulatory body and other interested parties that the site remediation or site release criteria have been met.

The measurement results of the monitoring process will inevitably show certain variability. This variability can result from:

— Uncertainties associated with obtaining single measurements;
— The true variability of the parameter being measured.

Measurement uncertainty is associated with monitoring techniques and Section 5.6 covers the evaluation of uncertainty in more detail. Comprehensive descriptions of factors that affect measurements can be also found in Ref. [19].

Variability of measurement results can be reduced, to some extent, if more precise measurement methods are available, but the true variability of the measured quantity remains. Both effects lead to an uncertainty of the final decision whether the site/survey unit complies with the established criteria or not. Different approaches are used to deal with the variability and uncertainties. To arrive at decisions that are defensible in both scientific and legal respects, it is generally considered necessary to apply sound statistical methods. Such statistical methods allow for specifying uncertainties and decision errors. The choice of statistical methods used depends on the circumstances discussed in more detail in the Bibliography.

An important question in this respect is whether the derived remediation criterion applies to an average condition (see Section 3.5) or whether it is to be

applied to every single measurement, or the area it represents, respectively. In the latter case, the uncertainty of the decision is governed more by the measurement uncertainty.

In many cases, averaging the measured quantity over each survey unit is appropriate (see Section 3.5). Under these circumstances, the uncertainty of the estimated mean values, statistical values by their nature, is the decisive quantity. It depends, among other things, on the variability of the data, analytical uncertainty and the sample size.

The use of hypothesis testing provides a means to deal with these uncertainties, although other methods exist (confidence intervals about the mean). The method to be used depends on a variety of factors (for more information, consult the Bibliography). Some fundamentals are presented in the following section. It should be noted that it is important, when monitoring for compliance, to define the conditions discussed in this section in the early planning phase because it has strong implications on, for example, the required sample size. Improper handling of these issues may result in expensive extra measurements, unnecessary additional remediation activities or an inefficient final remediation monitoring plan if the criteria are not met.

Other factors influencing uncertainty include:

— Uncertainty regarding the characteristics of the site and contaminated media, including imprecise estimates of volumes or masses, an imprecise knowledge of the levels of contamination, the mixture of radionuclides and the depth of penetration of contaminants (i.e. horizontal, vertical distribution).
— Human error: The operator's staff involved in the monitoring will inevitably contribute to adding uncertainties. For example, scanning measurements are often performed using ratemeters which have a display that shows a rolling average, based on the previous few seconds. The surveyor is confronted with an indication which varies even when the probe is held stationary, simply because of the random nature of radioactive decay. How each surveyor responds to subtle instrument indications may not be completely consistent.

It is also important that the operator takes into account the uncertainties that could arise from the fact that:

— The monitored area is surrounded by other areas which will contribute to the signal.
— Contamination may not be uniform over the area of the probe.

— The concentration of contaminant may depend on the depth in the monitoring volume and the actual material (e.g. soil is rarely uniformly mixed). Activity can start out on the surface by deposition from a plume and then be washed in by rain or moved by the action of earthworms and other biota. The area may have been covered with clean soil or been ploughed. If the deposition event occurred a long time ago, the concentration may increase with depth to a maximum value.
— The radionuclide vector will inevitably differ slightly from the initial radionuclide vector.

When planning the monitoring for compliance, the uncertainties associated with each measurement should be considered. The larger and more complicated a site, the more quality control (QC) measurements that are required. The more difficult the measurement, the more emphasis that is necessary during review.

3.9. HYPOTHESIS TESTING

The determination and testing of proposed hypotheses is an essential part of statistical inference. In order to formulate such a test, a theory is usually put forward, either because it is believed to be true or because it is to be used as a basis for argument, but has not been proved. An example is claiming that contamination identified in an area is above natural background concentrations in a similar or reference area.

In a statistical problem, the question of interest is simplified into two competing claims between which there is a choice. These are referred to as hypotheses. The null hypothesis is denoted H_0, against the alternative hypothesis, denoted H_1. The two competing claims are not treated on an equal basis; special consideration is given to the null hypothesis because the null hypothesis relates to the statement being tested, whereas the alternative hypothesis relates to the statement to be accepted if or when the null hypothesis is rejected. Generally, a hypothesis is stated in a manner where H_0 will be rejected. There are two common situations:

(a) The monitoring has been carried out in an attempt to disprove or reject a particular hypothesis, the null hypothesis, thus, priority is given to one hypothesis so that it cannot be rejected unless the evidence against it is sufficiently strong. An example of the description of the null hypothesis is: H_0 — there is no difference in concentrations of ^{238}U in the remediated area from a reference area; H_1 — there is a difference.

(b) If one of the two hypotheses is 'simpler', it is given priority so that a more 'complicated' theory is not adopted unless there is sufficient evidence against the simpler theory.

The hypotheses are often statements about population parameters, such as expected value and variance. The use of these parameters is defined by the particular statistical test that is to be employed for the evaluation of the data. The outcome of a hypothesis test is 'reject the null hypothesis, H_0' or 'do not reject the null hypothesis'.

Once the statistical test has been completed, the results are stated in terms of the null hypothesis. The conclusion is either 'reject H_0 in favour of H_1' or 'do not reject H_0'; the alternative hypothesis is neither accepted nor rejected.

If the conclusion is 'do not reject H_0', that does not necessarily imply that the null hypothesis is true but it suggests that there is not sufficient evidence against H_0 in favour of H_1. Therefore, rejecting the null hypothesis implies that the alternative hypothesis may be true but does not require it to be true.

The alternative hypothesis, H_1, is a statement of what a statistical hypothesis test is set up to establish. For example, following remediation, the alternative hypothesis might be that contamination in the survey unit does not exceed the derived concentration limit.

Typically, it is prudent to state the null hypothesis as "the contamination concentration in the sample set exceeds the derived contamination criteria." This puts a greater statistical burden on the operator to reject the null hypothesis as seen in the following section. If the null hypothesis is rejected, the implication is that the sample set does not exceed the derived concentration limit.

For additional guidance on hypothesis testing, see the Bibliography.

3.10. ELEVATED LEVELS

When conducting monitoring for compliance with the derived remediation criteria, it is not uncommon to find localized areas with levels that are higher (elevated levels) than the radiological criteria although the mean value of the survey unit may be well below the remediation criteria. This is taken into consideration in the design of the monitoring plan and considered in the decision making process for the compliance with criteria. When elevated levels are found, further characterization might be necessary to determine whether the survey unit meets the remediation criteria or whether further remediation is needed. For example, when using MARSSIM methodology, elevated levels might indicate that reclassification of the survey unit is necessary.

Measurement results that are below derived criteria but higher than the expected levels of the survey unit might indicate an instrument failure or improper classification of the survey unit.

The survey unit can be classified in terms of low, medium or high, as follows:

(a) Low: areas which are not expected to have levels of residual activity exceeding a small fraction (typically on the order of about 25%) of the derived remediation criteria;
(b) Medium: areas which are anticipated to have some level of residual activity but not exceeding the derived remediation criteria;
(c) High: areas which are known to have had levels of residual activity exceeding the derived remediation criteria prior to remediation, where site knowledge indicates prior operations and activities presented a high probability of contamination, or where professional judgement otherwise suggests that there may be locations of contamination in excess of the remediation criteria.

Scanning with monitoring instruments is usually performed to identify areas with elevated activities. The extent of such monitoring (e.g. whole site or part of the site) depends on the level of confidence that there could be areas with elevated activity after remediation is completed, i.e.:

— If the available information indicates that elevated areas were present before remediation or are potentially present at the site following remediation, 100% coverage of the scanning monitoring will be recommended during the final remediation monitoring;
— If the information provides confidence that such elevated areas were not present before remediation, a decision needs to be taken on the extent of coverage during the final remediation monitoring, which can range from 10 to 100%.

3.11. QUALITY MANAGEMENT

The quality management programme needs to address all aspects of the remediation activity, including final remediation monitoring. In this Safety Report, some sections include more detailed discussions of applicable quality management requirements. This does not minimize the importance of the quality concept as applied to other sections.

Quality management is an important aspect of final remediation monitoring for compliance with derived remediation criteria. Its aim is to ensure the quality of monitoring results and increase confidence in the demonstration of successful remediation. Quality management applies to the entire process of final remediation monitoring. It also provides for a disciplined approach to all activities affecting quality, including, where appropriate, verification that each task has met the requirements and any identified corrective action has been implemented. Quality management needs to satisfy the recognized standards established by the regulatory body (e.g. Ref. [15]) and include provisions from international standards (e.g. Refs [8, 10, 11]).

Many aspects of quality management that relate directly to the implementation of final remediation monitoring or the analysis of results are discussed in the relevant sections of this Safety Report and, in particular, Section 5.

It is important to note that a graded approach needs to be applied to the development and implementation of the quality management system, commensurate with the scope and complexity of the project. One fundamental aspect which affects the design of the QA programme is the level of reliance on sampling and radiochemistry. In some situations, it is possible to meet the derived criteria using only portable radiation detection instrumentation. However, some contaminants are not nearly so easy to detect and require sampling, possibly followed by radiochemical analysis [20]. This could include areas contaminated by pure alpha or beta emitters. Sampling is time intensive and radiochemistry is expensive. In such an example, a statistically guided sampling plan is essential to maintain effective cost control. This situation will emphasize the importance of the quality management programme and control measures for its implementation. An example guide for quality management applied to sample analysis can be found in Refs [9, 12, 20].

The operator needs to be able to demonstrate how the quality of the final remediation monitoring has been ensured. Quality checks on equipment qualification, regular auditing of external suppliers and checks on the performance of their own staff provide evidence of a sound programme. The approach to the influence of uncertainties in measurements close to a limit needs to be clearly documented.

Factors influencing the quality management of final remediation monitoring include:

— Number and location of measurements;
— Available experienced personnel involved;
— Current and historical performance of sampling and analytical procedures used;

— The variability of background;
— Number of contractors (e.g. laboratories) used;
— How close derived remediation criteria are to detection limits.

3.11.1. Quality management programme

The development of an effective quality management programme to support the remediation project is critical to the overall potential for success. The programme includes all factors that could affect the quality of the monitoring results; including contracting and procurement of critical instruments and equipment, training of personnel, audits and surveillance, document control, measurements and tests, etc. (see Appendix V).

Quality requirements may be captured on checklists (see Appendix VI) that are completed each time monitoring is performed. The checklists can then be reviewed by management or as surveillance at a later time. This surveillance provides important indicators about the overall effectiveness of the remediation project.

3.11.2. Data quality objectives

The data quality objective (DQO) process is an example of a systematic planning tool based on the scientific method using a graded approach to ensure that the level of detail in planning for the conduct of monitoring and the level of effort applied in conduct of monitoring are commensurate with the intended use of the resulting data and the degree of confidence needed in the results [21]. This process focuses the data collection effort on data that will lead to the decisions on whether the survey area meets the derived remediation criteria. Data that do not contribute to better decision making are unnecessary and costly. Focusing the final remediation monitoring on the important data needed for a decision will result in a selection of a specific action (e.g. unrestricted use) or an alternative action (e.g. restricted use) and will then lead to development of an effective monitoring plan.

3.12. RESOURCES

In order to plan and undertake monitoring for compliance with derived remediation criteria, clear allocation of responsibilities and adequate resources are required. A comprehensive management approach, thus, needs to be established to fulfil the planned final remediation monitoring in a timely manner with optimized benefits/costs ratios and according to national regulations.

The following subjects should be carefully considered in this approach:

— Identification of project responsibilities (see Appendix VII);
— Definition of available and required resources — personnel, equipment, and financial and scheduling constraints;
— Establishment and implementation of an appropriate quality management programme, including development of procedures for training personnel, testing equipment, etc.

3.12.1. Human resources

Resources other than identified instruments and analytical services will be required for monitoring for compliance with derived remediation criteria. Much depends on the size and nature of the final remediation monitoring task and the time available to perform it. Good management of a monitoring project will aim to demonstrate compliance with the derived remediation criteria and meet all of the constraints at a minimum cost. This means that the resources required must be evaluated at the planning stage of final remediation monitoring.

It is important to note that the monitoring for compliance is variable and that the more complex a site is, the more uncertainties that can be expected. Hence, if there is a tight deadline on completion of the final remediation monitoring, perhaps caused by the starting of construction work on the site after its release from regulatory control, the earlier the review exercise needs to be designed and, subsequently, completed. This will generally require more human resources to work on the monitoring project at any given time and, generally, a higher overall cost for completion.

It is also important to have clear lines of communication between the staff involved in the final remediation monitoring, so that areas of the site which fail to meet the derived remediation criteria are communicated to the person responsible for site remediation.

The operator's staff needed for the successful completion of the final remediation monitoring includes:

— Surveyors to perform the radiation measurements.
— Staff to maintain and test the equipment on-site.
— Supervisors to provide advice and also to check the quality of monitoring.
— A project manager with staff to maintain overall project controls.
— A health and safety representative to support work planning, monitoring for hazardous conditions and surveillance of work activities.

— A radiation protection engineer or scientist to develop special procedures, analyse results, etc. Responsibilities may include dosimetry and the ALARA (as low as reasonably achievable) programme.
— Staff for data processing and record keeping.

For small monitoring projects at small sites, all of these functions may be performed by one or two experts but, on larger projects, several members of staff may be required.

The level of skills, experience and training of the staff has to be appropriate to the complexity of the monitoring task. There has been much debate on whether it is best to employ monitoring staff with experience of the site when it was operating, if they are available, or whether it is better to employ staff trained particularly for site remediation monitoring. The advantage of the first case is local knowledge of the facility and operation, potential areas of contamination and unique characteristics of the site. The disadvantage is that because the operational staff worked with permissible higher exposure and contamination levels during facility operation, where requirements are based on occupational exposure, they may find it difficult to come to terms with the more stringent requirements of working with the much lower levels of exposure and contamination associated with the final remediation and potential site release, where requirements are generally based on unrestricted release.

The aspects that must be clear to all staff working on-site are:

— What they are there to do;
— What area they are working on;
— Why the work is taking place;
— What hazards are associated with the work, how they need to respond to emergencies either on their site or on any adjoining site;
— That safety is paramount;
— How to perform their task;
— Whom to report anything unusual to;
— How their equipment works and limitations associated with it;
— How to maintain and care for equipment;
— That close supervision is required and that the entire project is likely to be audited;
— That everyone is part of the team and that overall job quality depends on everyone;
— That questions are expected and suggestions welcomed by management and supervisors;
— That falsification of data is unacceptable and will result in serious penalties;

— That honest mistakes will be accepted, provided that they are reported as soon as they are noticed and appropriate corrections made.

The level of training will have to be at least sufficient to allow the individual to work safely and effectively. Further formal training is useful, particularly training leading to a nationally recognized qualification.

3.12.2. Equipment

Once the monitoring strategy is selected for a specific site, it is important to ensure the availability of all of the necessary equipment. This includes planning and arrangements for obtaining and analysing samples, and calibration and maintenance of the equipment (see also Section 3.7).

For a large, complex site, this could require significant funding for the purchase of instrumentation. In some cases, setting up on-site or mobile laboratories can be useful. For monitoring a large site, the following instrumentation and equipment may, generally, be required:

— Airborne instruments;
— Portable monitoring instruments;
— Automated monitoring systems;
— Laboratory detectors and electronics;
— Sampling equipment and sample analysis system;
— Sample receipt and preparation equipment;
— Miscellaneous supplies and equipment.

In certain cases, if an on-site laboratory is used, it will be necessary to obtain credentials or certifications for personnel and procedures before valid results can be accepted. This may take months to accomplish and, thus, requires adequate planning and scheduling of the final remediation monitoring activities.

3.12.3. Financial resources

The cost of compliance monitoring depends on the type and number of measurements and number of samples requiring analysis, as well as on the verification required (e.g. through independent measurements). The cost of monitoring a large, complex site will greatly exceed that for a small site that handled small quantities of a limited number of radionuclides. Major costs can be attributed to labour, monitoring and sampling equipment, and expendable materials, such as tools, sample containers, plastic bags, signs, labels, photographic films, protective clothing, etc. Additionally, services, such as

analytical measurements, drilling and coring, aerial land monitoring, and transport and expenses, could constitute a significant cost. A time schedule for the entire final remediation monitoring is necessary to complete the total estimated cost of the project. Each project task needs to be included in the schedule and the associated costs need to be estimated separately.

According to the sequence of monitoring tasks, the costs can be grouped as follows:

(a) Preparatory costs for development of the monitoring strategy, staff training and, if necessary, obtaining the approval of required competent authorities.
(b) Sampling costs for obtaining surface soil samples largely reflect labour cost. A relatively minor investment will cover the cost of sampling tools. Obtaining subsurface samples requires additional effort and expenditure if depths beyond 3 to 5 m have to be sampled; this generally requires a motorized drilling rig. Occasionally, it is necessary to drill through asphalt, concrete or some other barrier to reach soil that needs to be sampled. As such drilling requires specialized equipment, costs are considerably higher than for soil sampling alone. In addition, it is generally necessary to patch holes drilled in such barriers to restore the surface, which would probably increase the total costs for this sampling.
(c) Analytical costs, e.g. sample analysis costs, are subject to great variability depending on the type of analysis, the number of samples and the level of radioactivity to be assayed. Analysis of a sample for a single radionuclide may present little difficulty, while analysis of the same sample for a large number of radionuclides would be difficult and, consequently, expensive. Costs of sample analyses may constitute a major section of the total final remediation monitoring costs.

3.12.4. Other resources

Other resources that are required for the successful performance of final remediation monitoring in terms of buildings and equipment include:

— Staff washing and changing areas, as well as first aid supplies.
— Processing space: Where sampling is anticipated, there will need to be a dedicated area where samples are either processed and counted or where they are packed for dispatch to a laboratory.
— Space to produce maps and data summaries.
— Spare instruments and a place to store them safely.

— Protective equipment: Normally, for final remediation monitoring, there is little chance of significant surface and airborne contamination. However, wind and weatherproof clothing, and waterproof boots and gloves are needed for outside work. Where there is traffic, high visibility clothing is useful. Where there is work going on above ground level, hard hats are important. Even work in intact buildings will require coveralls to control dust. In unusual cases, final remediation monitoring may be being carried out while other pollutants, such as asbestos, are being excavated. In that case, the monitoring staff will have to be equipped to be protected against exposure to other hazardous materials.

Outside services may also be required and these may include:

— An instrument calibration, test and repair service.
— An analytical laboratory and associated courier service.
— Waste (radioactive or non-radioactive) removal, as even small projects will generate office and restroom waste. Projects which involve sampling may also produce chemical waste from laboratory processing, such as liquid scintillation counting.

3.13. RECORD KEEPING

A considerable fraction of the final remediation monitoring involves the generation, collection and record keeping of monitoring results which need to be managed as part of the quality management programme. These results need to be checked for credibility and authenticity, and then reliably stored for as long as requested. For a small project, the fieldwork can be stored in one notebook and the analytical results in one folder in a filing cabinet or one folder in a database. However, for major projects, the data stored can run into millions of individual readings. Additional discussion on this subject is provided in Section 5.

For large projects, the aim is to optimize record keeping and archiving. As far as possible, all of the information relevant to safety and confirmation of monitoring results needs to be stored, preferably automatically. For example, surface gamma measurements can be stored and processed in a geographical information system, with the various count rates recorded against a global positioning system (GPS) position and time. Samples can be barcoded, with the sample location stored by GPS, and the sample followed through by barcode. However, for measurements performed by hand-held instruments, it is not so easy. One approach is to design a monitoring sheet with a clearly identified space for each measurement. These can be photographed and stored as a computer file.

Another approach is to enter the data directly from the instrument onto a palm-top. This minimizes transcription errors but can be slow and inconvenient in the field. At a minimum, any paper data need to be stored until they have been recorded in a database and until that database has been backed up on a secure server. In any case, a backup copy of all relevant information is needed.

The right of entry of data needs to be robustly controlled to avoid deliberate or accidental corruption. Given the tendency for digital data storage media to be popular for a limited period of time, the final report and fundamental data need to be printed out on acid free paper and then archived in a secure store, at least in accordance with the regulatory body requirements.

3.14. NON-RADIOLOGICAL HAZARDS DURING THE CONDUCT OF FINAL REMEDIATION MONITORING

Any work produces some level of risk. At the planning stage for the final remediation monitoring activity, it is important to identify sources of risk to the workers, usually the technicians performing the monitoring, but also to management and others who may be in the areas, such as personnel from the regulatory body, etc. and to establish work controls to minimize risks to an acceptable level. Following remediation, the site may pose significant hazards as buildings may have been demolished, drain lines removed, soil excavated, etc. Examples of non-radiological hazards include:

— Slips, trips and falls, particularly in areas where there has been earth removal and demolition.
— Water, where the site either includes or is bounded by water of any depth.
— Traffic, where the site is in active use.
— Buried electrical services, gas pipes, etc., particularly when sampling.
— Chemicals and heavy metals that may result from the processes involved in the purification of radioactive material. Sometimes, other activities on the site may have used hazardous chemicals. This is particularly likely for industrial sites which were in use before radioactivity was processed.
— Wildlife, such as snakes and poisonous insects or plants.

A programme addressing industrial (non-radiological) hazards will be required by the regulatory body for the development of a formal health and safety plan, or equivalent, for the remediation activity, so that industrial safety is fully considered and integrated into the planning and execution of all work processes, including the performance of monitoring. Appendix VIII includes an example of

a work permit that includes safety and radiological controls, and that can also be applied to final remediation monitoring.

3.15. SELECTION OF AN OPTIMUM STRATEGY FOR FINAL REMEDIATION MONITORING

Before a remediated site can be released from regulatory control for restricted or unrestricted use, it must be demonstrated with a significant level of confidence, acceptable to the regulatory body, that residual radioactivity satisfies established radiological criteria. This assurance is achieved through selection and implementation of an optimum strategy for final remediation monitoring for a particular site followed by a data evaluation process that yields a defensible decision regarding the area's radiological status after completion of remediation.

The appropriate evaluation and consideration of the aspects outlined above and in this section will lead the operator of a site to the selection of an optimum strategy for final remediation monitoring of a site after completion of remediation. This strategy needs to be adopted for monitoring for compliance activities depending on the nature and contamination of the site and on the nature of the remediation performed, considering the factors discussed in Sections 3.1 through 3.13. The strategy will have to be flexible, given that there may be unexpected findings (e.g. subsurface contamination) which may require the monitoring strategy to be reviewed and revised.

In addition, there are factors that also need to be taken into account before implementing the monitoring strategy.

3.15.1. Physical site characteristics

The physical characteristics of the site have a significant impact on the complexity, schedule and cost of final remediation monitoring. These characteristics include total area, topography, soil type and ground cover, as well as the number and size of structures both above ground and underground, type of building construction, etc. If the site does not have obvious physical boundaries, such as a fence or roadway, then it will be essential that the site boundaries are identified.

3.15.2. Access to the site

The operator needs to exactly identify the area to be monitored for compliance with derived remediation criteria and needs to ensure that all interested parties are prepared to allow access to the site for the purpose of the

monitoring. This may require significant notice if the site is within, for example, a secure area or where other interested parties have to be informed. If the site does not have obvious physical boundaries, such as a fence or roadway, then it will be essential that the boundaries are easy to identify.

Accessibility of land areas has a significant impact on the monitoring effort. For example, on a large site where the major contaminant is an energetic gamma emitter, an easy and fast way to monitor can be to use a vehicle mounted detector array. If large areas of the site are difficult to access, then monitoring will be conducted by hand, which significantly increases the time required. Sites with many trees may also pose problems, both in terms of access for vehicles and because trees interfere with GPS based mapping systems.

Once the available information is reviewed, the site needs to be visited by the person developing the monitoring plan. This is essential as it gives a clear idea of the task ahead and may identify weaknesses in the original information or suggest means whereby monitoring could be simplified.

3.15.3. Physical non-homogeneity

The issue of non-homogeneity needs to be considered on the basis of the type of site. Land based sensing techniques have a maximum lateral range of 50 cm and a vertical depth range of about 30 cm. Sampling procedures will normally take a sample from a few square centimetres and may go down in incremental depths up to 4 m [22]. Large structures, such as concrete or brick bases in the ground, are easily visually differentiated from the surrounding land. It is important to consider any non-homogenous effects that may interfere with compliance scanning or direct measurement procedures and develop a method to cope with them. For instance, if a thin concrete base is laid on the ground surface after the area was remediated, a suitable procedure to ensure that an accurate assessment of residual contamination under the concrete needs to be made.

3.15.4. Challenges

The main challenge in monitoring for compliance is to concentrate on important aspects, such as:

— The level of confidence in the workers who are performing the remediation is important. A generally experienced worker, familiar with the type of job and with a good record, is unlikely to make major mistakes. A less experienced worker or a particularly unusual or difficult task has a higher chance of failure. One approach is to look in more detail and earlier at areas where a higher possibility of failure is anticipated. If the remediation task

has been done well in these areas, then both the possibility of failure and the consequences will be minimized as less difficult areas are investigated. Another approach is to follow the worker through the monitoring process. This means that early areas, where the worker was gaining experience, will be checked first. It also means that areas the worker cleared first will be monitored again.

— The level of confidence required by the regulatory body.
— Any possibilities of recontamination that may have occurred during the monitoring for compliance. Verification checks are useful in detecting these events.
— Measurements that were difficult with the techniques used during the planning stage or during the process of remediation. For example, if a vehicle mounted detector array was used for the majority of the site monitoring, hand-held measurements would be performed under trees and bushes and close to buildings. These measurements may not have been performed so well and are certainly more difficult to audit. Buildings may also enhance the local gamma background, making it more likely to miss a relatively small increase in count rate caused by contamination.
— Consideration of where activity may have been concentrated during normal operation. For example, loading fuel transport flasks from a road vehicle to a railcar may result in paint being chipped off. These flakes, which could have contamination, may then be washed into an area and concentrated.
— Potential failure to remove contaminated services, such as drains and cable ducts, because they were not on the site plan. This is particularly common on old (historical) sites which may have been taken over from another user. A careful walk through the site will sometimes find these.

3.15.5. Graded approach

It is important to realize that remediation projects vary significantly in size, from a few square metres up to many square kilometres. Recommendations stated in this Safety Report may consequently be applied, taking into account the size of the project applying the graded approach. The development of a compliance monitoring programme needs to be commensurate with the level of contamination of the site and its intended use. If the site will be used for the purpose of a new authorized practice, the criteria could be different than if it is meant for unrestricted use.

In monitoring for compliance with remediation criteria, the basic premise is that areas most likely to be contaminated require more attention than those which are less likely to be contaminated. Therefore, throughout the planning process, a ‘graded approach’ is employed to concentrate efforts where the potential for

contamination in excess of established derived remediation criteria is greatest and/or the potential consequences of residual contamination may be of highest concern.

Example: A site 50 000 m^2 in area was used for an operation with ^{137}Cs, for which the regulatory body authorized a release value of 0.1 Bq/g. Characterization identified 5000 m^2 of contamination in soil in excess of 0.1 Bq/g. That area was remediated to remove the contaminated soil. The remaining 45 000 m^2 of the site contained small areas of ^{137}Cs contamination, above 0.05 Bq/g, but no contamination was identified on this 45 000 m^2 above 0.08 Bq/g. In accordance with the process described here, the area of 5000 m^2 which required remediation would be classified as high contamination potential in accordance with Table 2 and the remaining 45 000 m^2 would be classified as medium contamination potential. In keeping with the concept of the graded approach, areas with a low potential for contamination will be monitored with a lower degree of rigour than those with higher contamination potentials. The 5000 m^2 would be monitored over 100% of the surface area. The remaining 45 000 m^2 would be monitored at a lesser frequency, perhaps 10–50%. By subdividing the area into survey units, it would be possible to monitor survey units with the greatest potential at 50% coverage and those with lower potential at perhaps 10% coverage.

It is important to recognize that the regulatory body may also consider applying the graded approach to regulation and control of remediation activities through specification of a different set of requirements for final remediation monitoring for different situations of contaminated sites, e.g. Ref. [18]:

- Facilities, where radioactive material was used in a way that would preclude its release into the environment and is not expected to cause activation of adjacent material or contamination of work areas (use of sources without leaks, use of radionuclides with a short half-life, etc.);
- Facilities with residual radiological contamination in building surfaces and soils (e.g. leaking sources, unsealed radioactive material use leading to contamination below screening criteria);
- Facilities with radiological contamination of buildings and soil (not underground water) not meeting the derived remediation criteria;
- Facilities with residual radiological contamination present in buildings, soil and groundwater;
- Facilities with residual contamination in buildings, soil and groundwater exceeding the established derived remediation criteria.

Using this approach assumes that building surface and soil surface contamination screening values are in place for the radionuclides of concern. If

there are specific radionuclides at the site for which no screening values were defined, screening levels need to be derived using approved or agreed modelling approaches and tools (e.g. Ref. [18]).

A graded approach needs to be developed in order that the monitoring effort is commensurate with the expected residual contamination at the site that has been remediated and the cost–benefit analysis has been performed. The practical application of the graded approach leads to:

— Optimization of the health and safety of workers and public;
— Reducing burden to future generations;
— Optimization of the number of measurements;
— Optimization of costs.

3.15.6. Involvement of interested parties

The ultimate objective of site remediation and associated final remediation monitoring is to demonstrate compliance with established criteria for unrestricted or restricted use. Thus, the number of concerned and interested parties (also referred to as stakeholders) is generally greater than that for routine operations of facilities using radioactive material. In order to implement remediation and compliance monitoring effectively and smoothly, it is necessary to identify the interested parties and to obtain their advice in each step of designing the monitoring strategy. For example, in establishing the derived remediation criteria, agreement by the regulatory body is required. At that time, the implication of proposed derived remediation criteria needs to be explained to the relevant interested parties. The same process for communication/information is needed when the monitoring strategy to demonstrate compliance with the derived remediation criteria is being planned.

It is important that information provided to interested parties is thorough and accurate, and is communicated through a clear and transparent process. It is also necessary that comments and concerns be resolved in the same manner and that modifications to the monitoring strategy correctly reflect the resolutions reached.

4. IMPLEMENTATION

The implementation stage of final remediation monitoring comprises of real time instrument response and the collection of samples with subsequent analysis. In reality, planning of final remediation monitoring commences with the performance of the characterization and scoping surveys. The acceptability of the data that were collected during these stages may be limited if this monitoring was not planned and conducted with the thought of providing usable data for the final remediation monitoring.

The various media that need to be considered following remediation include:

— Surfaces of structures and buildings;
— Soil;
— Construction material, fill, drains, etc., to be left in the ground;
— Surface water, including standing water on the site and any drainage from the site, and groundwater from local and regional water tables;
— Air, particularly where the main exposure route for future receptors is by airborne activity, for example, radon and its progeny;
— Other types of media that include fauna, flora, etc.

4.1. APPLICATION OF MONITORING STRATEGY

The operator is the main factor in the effectiveness of final remediation monitoring. The performance of the operator is based on the consideration and appreciation of the elements described in Section 3.1.

The use of a recognized process for systematically addressing the considerations associated with a remediation project provides assurance that the goals have been clearly defined. An example of this type of process is the DQO process described in Section 3 [23, 24].

4.1.1. Understanding the radiological criteria

The remediation plan needs to describe the radiological criteria clearly. If the site is split into survey units, a sketch or drawing needs to be produced that clearly identifies each with sufficient clarity so that the regulatory body can identify which monitoring point belongs to each survey unit. Each area must have an established radionuclide vector, as appropriate, plus one or more of the following derived remediation criteria:

— An activity concentration together with a corresponding permissible averaging area and depth. If any other materials are present, such as water or construction materials to be left in situ, there needs to be a corresponding averaging mass or volume specific to these materials.
— A surface activity for identified objects or materials, together with a defined averaging area [25].
— A limiting dose rate or exposure rate (air kerma rate).
— A limiting single object total activity, particularly when dealing with objects such as luminescent dials or other high specific activity items.
— An airborne concentration, particularly when dealing with radium contaminated materials.

4.1.2. Selection of reference areas

Derived remediation criteria may be expressed in terms of concentration levels above background for specific radionuclides. If contaminants of concern are also present in background at levels, which are significant relative to the derived remediation criteria, it is necessary to select reference areas such that the site data can be compared to radionuclide contributions to determine the average level of residual radioactivity of the site. The reference area is defined as an area that has similar physical, chemical, radiological and biological characteristics as the survey unit(s) being investigated but has not been contaminated by site activities. Reference areas are normally selected from non-impacted areas but are not limited to natural areas undisturbed by human activities.

The relation between the radionuclide contribution in the reference area and its variation to the derived levels needs to be considered in the decision making process, including the decision rule and the selected statistical tests.

Data from measurements at the site before it was potentially contaminated are useful when available. Although not a common practice in the past, new installations commonly measure and sample building materials and the site area prior to construction to provide a baseline for future decommissioning or remediation.

Certain radionuclides including members of the naturally occurring uranium, thorium and actinium series, as well as ^{40}K, ^{14}C and tritium may occur at measurable levels in the background. Caesium-137 and other radionuclides are also present in the background as a result of nuclear weapons fallout or nuclear accidents. It needs to be emphasized that, for a site which can contain significant levels of natural radionuclides (e.g. in certain construction material, fertilizers, etc.), it may be difficult to select a reference site comparable with the one to be monitored. The natural variability of the radionuclide content of such a site is often large and the assessment of the background levels may require a large

number of measurements in order to obtain meaningful statistical distributions. For example, this may present a concern if radium concentrations in soil create radon and radon daughter levels which vary with time.

For statistical reasons, it may be necessary to have an equal number of samples from the survey unit and the reference area (referred to as 'paired samples'). This means that for each sample collected, or measurement taken, a corresponding sample or measurement from a reference area is required. For large remediation areas with many survey units, it may be difficult to identify qualifying reference areas because of the large number of paired samples required.

In cases where there may not be enough unique reference area samples for all of the samples from the survey units, it is possible to pair several survey units with one set of reference samples. However, statistically it is possible that samples from the reference area may cause the survey unit to fail when in fact the unit did pass (Type II error, see the Bibliography). If a number of survey units have been linked to this reference area, then all of the survey units may fail and so this practice has an associated higher risk.

4.1.3. Choosing the correct monitoring techniques

Monitoring techniques depend on the specific radionuclides, allowable residual contamination levels, distribution of the radionuclides in the matrices, instrumentation capabilities (Appendix IX), time and cost for monitoring, environmental factors, including accessibility to the areas to be monitored, and level of performance as defined in the approved remediation plan.

The measurement capabilities of the instruments need to be compared with the guideline values (e.g. an established fraction of the derived value). If the minimum detectable activity (MDA) is less than the guideline value, this instrument is suitable for consideration for use in the final remediation monitoring.

For example, a small area (~2 ha) on a rather flat site with generally non-porous soil (high clay content) was recently contaminated by a single radionuclide that is easily measured, such as ^{137}Cs. Instrumentation — a 5 cm by 5 cm diameter NaI(Tl) detector coupled to a scaler/ratemeter — is available. Trained technicians are commissioned to conduct the monitoring. The monitoring techniques will include a selection of a reference area and monitoring in both ratemeter and scaler modes, followed by collection and gamma spectroscopic analysis of the background samples. The area that was remediated is monitored to include scanning in ratemeter mode, stopping and taking measurements in scaler mode for elevated readings, and perhaps collection of samples of specified size using prescriptive directions. The samples are then analysed by gamma

spectrometric methods by a qualified laboratory that generates data of acceptable quality.

In more complicated cases, such as the case of weak beta emitting radionuclides, e.g. ^{63}Ni, instrumentation may not provide measurements adequate to meet the derived remediation criteria. In these cases, sampling, combined with historical knowledge and any other potential indicators may be necessary to demonstrate compliance. In any event, the approaches and techniques are formally described in approved, documented procedures.

Monitoring can be accomplished, for example, by the following approaches:

— In situ measurement, where the equipment is taken to the area of interest and the measurement is performed with the material in its natural place: This method can be the cheapest and simplest, if the end state and radionuclide vector are appropriate. For example, on a site contaminated with radium luminescent dials at or close to the surface, monitoring with a gross gamma detector is appropriate. This can be accomplished by a radiological survey[3], either a walk-over survey, a vehicle survey or an airborne survey.
— Sampling and processing on-site: This is useful when it is difficult to make measurements in situ but where no complicated sample preparation is needed. A good example is potential contamination by depleted uranium. This has a low gamma output but an energetic beta emitter. Soil samples can be taken, anything (such as twigs, pieces of metal, wire) which could damage a relatively thin windowed detector removed, the cleaned material placed in a sample tray, rolled flat and then counted with a large area, background shielded, beta detector for perhaps 100 s, depending on the derived remediation criteria.
— Sampling, followed by off-site processing: This is used where it is too difficult to do analysis on-site and also to verify on-site measurements. It is employed for difficult to measure radionuclides, such as plutonium alpha activity in soil with a high, natural uranium content.
— Long term measurement by integrating dosimeters.

On most sites, a combination of these techniques will be employed but the contractor has to clearly demonstrate the logic of the choice for the methods employed.

[3] The term ‘radiological survey’, as used in this publication, means an evaluation of the radiological conditions and potential hazards associated with the production, use, transfer, release, disposal or presence of radioactive material or other sources of radiation [6].

4.1.4. Measurement or sampling point selection

Following remediation, the residual contamination will typically be near background levels. For the purpose of the design of the final remediation monitoring, it is assumed that residual contamination will be uniformly distributed within a survey unit. To ensure that this is the case, some directed monitoring may be appropriate. It might be worthwhile monitoring the entire remediated area if instruments with sufficient detection capability exist. This monitoring may be supplemented with sampling.

Sample accuracy and precision are important considerations. Sample accuracy is related to the number of samples collected from a survey unit. Sample precision is related to the representativeness of the sample location to the distribution of contamination within the survey unit[4]. For remediation where the residual contamination is well below the derived remediation criteria, sample precision is less important and may not be cost effective. However, sample accuracy is always critical. Sample accuracy is achieved by applying an appropriate statistical approach to the number of samples collected and the location. Random sampling methods are appropriate to use for determining the number and location of points for monitoring for both surface and volume residual contamination when it is impractical to provide 100% monitoring [24].

Once the number and location of the monitoring points have been established on a map, it is necessary to choose a means of locating the points on the ground. The easiest way outdoors is to use GPS. It is quick, simple and does not require measurement points to be marked on the site. If this is not practical, conventional monitoring methods can be used, with pegs placed at regular intervals from which individual sampling points can be determined. Small areas can be marked out with road marking spray paint.

The easiest sampling grid is squares (Fig. 10) but there are other approaches, such as the triangular grid (Fig. 11), which produce better effective coverage because the mean distance of any point from the monitoring point is less than with a square grid (Fig. 10)

For buildings, it is often difficult to specify a method for locating monitoring points, depending on factors including size, nature, potential for residual contamination, etc. For example, in rooms where unencapsulated radioactive material was processed, it may be appropriate to establish a 1 m by

[4] In sampling, ‘sample precision’ and ‘sample accuracy’ are commonly used terms. In analysis, these terms have been superseded by the terms ‘precision’ and ‘bias’, the combination of which leads to accuracy in analytical results (see Section 5.3 for a more thorough explanation of analytical accuracy).

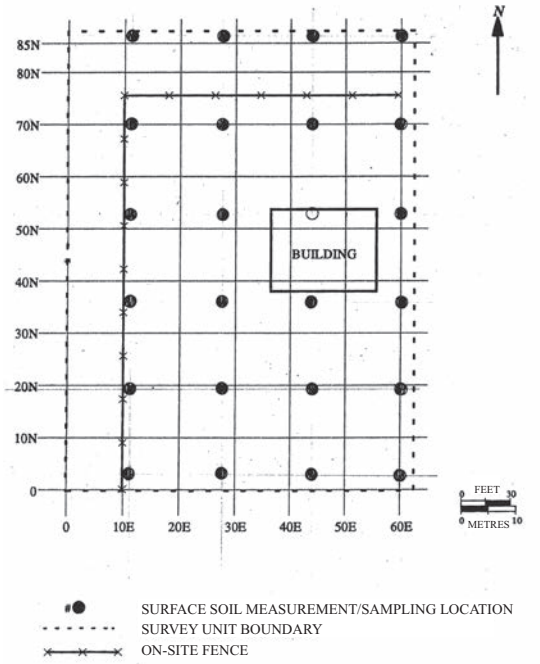

FIG. 10. Example of a square sampling pattern [9].

1 m grid on walls, floors and ceilings, and select sample points within the numbered grids. For a structure with low probability of residual contamination, it may be appropriate to locate sample points by measuring with a tape measure from a known point.

An example of determination of the number and location of sampling points is provided in Ref. [18].

4.1.5. Sample considerations

The selection of sample point density depends on the radiological criteria adopted and the anticipated probability that any point exceeds the derived remediation criteria in terms of either instrument response or sample analysis results. The higher the probability is, the more intensive the monitoring effort required.

Composite samples may be used in certain circumstances, particularly where the chance of elevated levels is low and in the case where the cost of sampling is low but the cost of analysis is high. It is then feasible to take multiple samples from the defined averaging area, combine the samples, and after

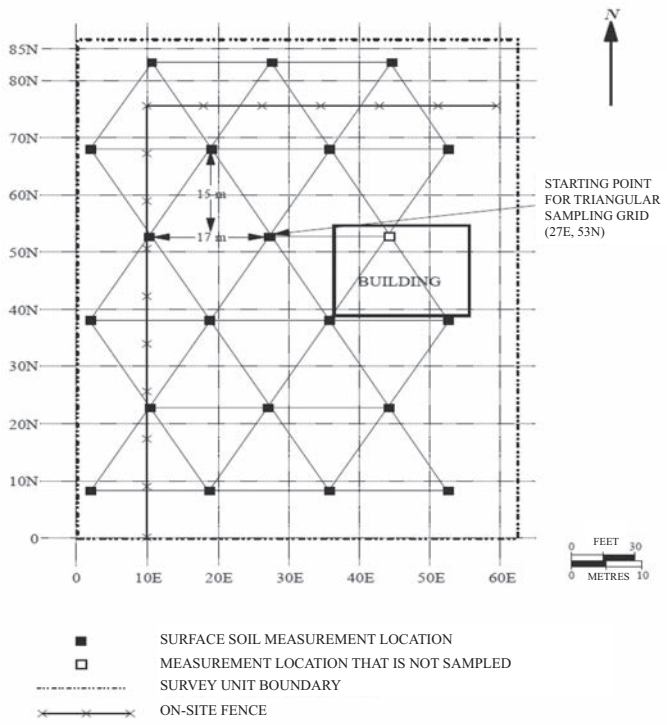

FIG. 11. Example of a random start triangular grid measurement pattern [9].

complete mixing, take an aliquot for analysis. This will produce a credible average value for that area, but care in the interpretation of the results is important. The results need to be mapped and trended. If the average readings and the standard deviation of the sample values do not change significantly from area to area, and the average does not indicate that any of the contributing samples would exceed the release limit, then the continued utilization of this method may be acceptable.

In the situation where the analytical cost is high and where there is a significant possibility of elevated levels on the area in question, then methods for screening 100% of the area are appropriate. It is necessary, in this case, to estimate the level of detection of the monitoring method so that an upper bound can be put on the potential missed activity. Based on this knowledge, the number of samples for a given survey unit can then be determined.

Results definitely meet derived remediation criteria	It is questionable whether results meet derived remediation criteria	Results definitely do not meet derived remediation criteria
(Acceptable)	(Uncertainty too great)	(Unacceptable)

FIG. 12. Main groups of monitoring results.

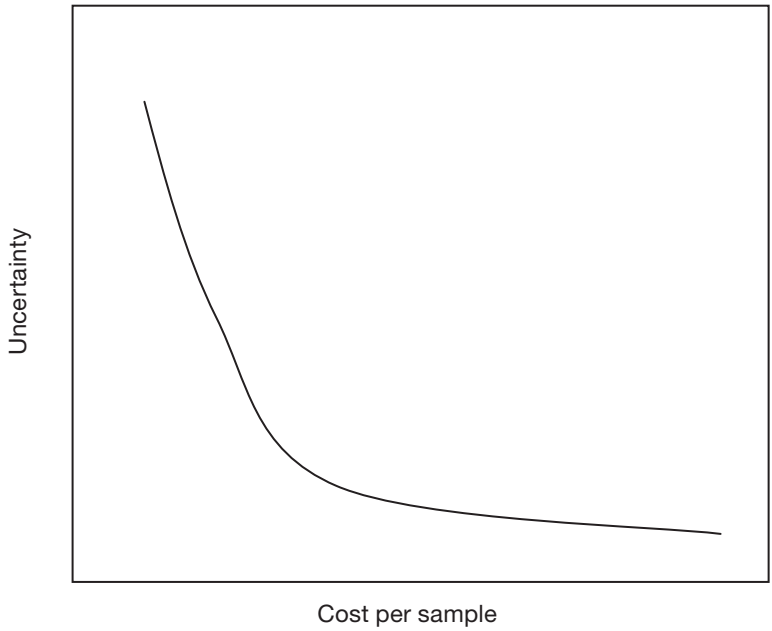

FIG. 13. Dependency of uncertainty of measurements with the cost for the desired quality.

4.1.6. Optimization of monitoring

The results of measurements can be described as falling into one of three categories (Fig. 12).

The monitoring strategy for compliance with remediation criteria will need to provide means for reduction of the uncertainties and, at the same time, increase confidence that the results meet the derived remediation criteria. The skill in planning of the monitoring is to minimize the cost for the desired quality of result (Fig. 13).

The initial cost to develop procedures, train personnel, acquire and qualify instrumentation, develop statements of work for analytical processes, etc. are significant. If these are used for a few monitoring locations, the cost per monitoring location is high. However, if a large number of monitoring locations is necessary, the cost per monitoring location decreases proportionately. The cost decrease eventually levels out as the cost to perform monitoring becomes significant compared to the initial cost per monitoring location. Uncertainty is directly related to the number of monitoring locations and, hence, the cost of monitoring.

The uncertainty drops rapidly as the cost increases but beyond a certain point, the rate of decrease of uncertainty slows dramatically. To enhance effective planning for final remediation monitoring, the scope and approach to the monitoring must be integrated with the development of the remediation plan and possibly include data from the characterization and from the monitoring of the remediation activity.

4.2. USE OF INSTRUMENTATION

It is important to explain the use of specific instruments in detailed procedures (see Appendix X). This includes choosing averaging, or integrating times and making use of any energy selection available to minimize the overall measurement uncertainty. This is common practice for gamma monitoring, where counting the photo peak for the radionuclide of interest is routine when dealing with materials with significant natural gamma activity. It is possible to use liquid scintillation in some cases to differentiate between beta emitters in a similar fashion.

The instrumentation used in performing the final remediation monitoring may be the instrumentation used during the remediation. It is preferred that instrumentation used for final remediation monitoring has a detection limit of less that 50% of the derived remediation criteria. This is not always possible and it may be necessary to apply a statistical process to the results.

The same principle applies to the use of instruments used for in situ measurement and sample analysis. Typically, 1 m^2 of ground will take approximately 1 s to monitor using a gross gamma monitor. If sampling is chosen, collecting the sample will take approximately 1 min, transporting the samples to a local monitoring station will require a few minutes every hour or so, and preparing and counting each sample will take a few minutes. Hence, even moving from an in situ measurement to sample collection followed by on-site measurement will increase the time required per unit area by a significant factor. These aspects are summarized below in Table 3 for gamma measurement.

TABLE 3. MONITORING STRATEGIES FOR GAMMA MEASUREMENTS

Parameter	In situ	By sample
Area monitored	Not well defined	Exact
Depth monitored	Not well defined	Exact
Background	Variable from measurement to measurement (unattenuated)	Defined (shielded)
Processing time per point	Few seconds	Minutes at minimum
Time for result	Instantaneous	Minutes to days
Auditability	Good, with proper instrumentation qualification and GPS data attached	Good only when GPS or equivalent data attached
Automatic mapping	Good, with GPS data attached	Requires additional effort, even with GPS data attached
Gamma spectroscopy processing	Simple analysis is available, field high purity germanium units are becoming more popular	Very high level of processing available; better analytical reports prepared as a rule
Hot particle detection	Good, if monitoring is conducted with that objective considered	Ineffective

The instrumentation must be used in a consistent manner as described in approved, documented operator's procedures by trained personnel who understand the subtleties of monitoring low levels of radiation. To ensure that instrumentation is used correctly, it is necessary to develop approved, documented procedures. These procedures include:

— How to check the instrument before use (general condition, battery, background, response to a check source);
— Where and when to use the instrumentation, including limitations in various environmental conditions;
— How to use the instrumentation — monitoring distance for contamination monitors, range selection, function selection, use of audible output, use of alarms, scan speeds and response to detection levels, use of time integrated measurements, etc.;
— Potential problems and limitations;
— Functional checks following use;

— Reporting requirements when an instrument fails a source or performance check.

Specific procedures may be needed to augment existing procedures for different radionuclide vectors, changes in matrices or perhaps changes in environmental conditions.

4.3. MONITORING

4.3.1. In situ monitoring

In situ monitoring includes the direct measurement of activity in the media, including surfaces and soil. In situ monitoring can be performed for most alpha, beta and gamma emitting radionuclides. The area monitored can be small (fractions of a square centimetre) to large (hundreds of square kilometres). In situ monitoring does not include sampling for subsequent analysis. Additional information on practical applications for monitoring of items and materials, and evaluating the contamination levels against established exclusion, exemption or clearance criteria can be found in Ref. [13].

4.3.1.1. Direct measurement of surface activity

Direct measurement of surface activity is performed in accordance with established standards, such as those in Refs [22, 26]. However, there are differences between measurement techniques for bulk material and land, as discussed in the following sections and Table 4.

4.3.1.2. Surface activity measurements of soil

To conduct direct measurements of gamma radiation, instruments and techniques providing the required detection sensitivity are selected (see Appendix IX). The type of instrument and method of performing the direct measurement are selected based on the type of contamination present, the measurement sensitivity requirements and the instrument derived remediation criteria. Direct static measurements are taken by placing the instrument at the appropriate distance above the surface (Fig. 14), taking a discrete measurement for a pre-determined time interval (e.g. 10 s, 60 s, etc.), and recording the reading. A 1 min integrated count technique is a practical field monitoring procedure for most equipment and provides detection sensitivities that are below most derived

TABLE 4. SELECTION OF DIRECT MEASUREMENT TECHNIQUES BASED ON EXPERIENCE

Radionuclide	Structure surfaces	Land areas	Direct measurement instruments		
	Detectable	Detectable	Surface activity	Soil activity	Exposure rate
H-3	No	No	ND	ND	ND
C-14	Yes	No	GPβ	ND	ND
Mn-54	Yes	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
Fe-55	No	No[c]	ND	ND (ISγ)	ND (ISγ)
Co-60	Yes	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
Ni-63	Yes	No	GPβ	ND	ND
Sr-90	Yes	No[c]	GPβ, GM	ND	ND
Tc-99	Yes	No	GPβ, GM	ND	ND
Cs-137	Yes	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
Eu-152	Yes	Yes	GPβ, GM	γS, ISγ	PIC, γS, ISγ
Ra-226 (c)[a]	Yes	Yes	GPα, αS	γS, ISγ	PIC, γS, ISγ
Th-232 (c)[a]	Yes	Yes	GPα, αS, GPβ	γS, ISγ	PIC, γS, ISγ
U[b]	Yes	Yes	GPα, αS, GPβ, ISγ	γS, ISγ, GPβ	PIC, γS, ISγ

TABLE 4. SELECTION OF DIRECT MEASUREMENT TECHNIQUES BASED ON EXPERIENCE (cont.)

Radionuclide	Structure surfaces	Land areas	Direct measurement instruments		
	Detectable	Detectable	Surface activity	Soil activity	Exposure rate
Pu-239 Pu-240 Pu-241	Yes	No[c]	GPα, αS	ND (ISγ)	ND
Am-241	Yes	Yes	GPα, αS	γS, ISγ	PIC, γS, ISγ

Note: GPα = gas flow proportional counter (α mode), GM = Geiger–Mueller survey meter, GPβ = gas flow proportional counter (β mode), PIC = pressurized ionization chamber, αS = alpha scintillation survey meter, γS = gamma scintillation (gross), ISγ = in situ gamma spectrometry, ND = not detectable.

[a] For decay chains having two or more radionuclides of significant half-life that reach secular equilibrium. The notation '(c)' indicates that the direct measurement techniques assume the presence of progeny in the chain.

[b] Depleted, natural and enriched have different properties which will influence the choice of instrument.

[c] Possibly detectable at limits for areas of elevated activity.

FIG. 14. An example of conventional scanning during remediation.

remediation criteria for many radionuclides. However, longer or shorter integrating times may be warranted.

Direct static measurements in the survey unit are taken at random locations specified in the final remediation monitoring plan. Alternatively, direct static measurements may be taken at systematic locations and supplement scanning monitoring for the identification of small areas of elevated activity. Direct static measurements may also be taken at locations identified by scanning monitoring as part of an investigation to determine the source of the elevated instrument response. Professional judgement is often used to identify locations for direct measurements to further define the real extent of contamination and to determine maximum radiation levels within an area, although these types of direct measurements are usually associated with preliminary monitoring, e.g. scoping, characterization and remedial action support. All direct static measurement locations and results are documented in accordance with the quality management requirements.

Due to their properties, direct static measurement of alpha and beta activity on soil surfaces generally has poor sensitivity and the results are often only qualitative. Other site surfaces, such as paved areas or structures and objects, may yield useful direct alpha and beta measurements, but such measurement types require instrument qualification prior to the measurements being scheduled [27–29].

Gross gamma measurements (e.g. using scintillation detectors) can provide a high level of detection sensitivity for certain radionuclides, and may be made more radionuclide specific by the use of a gamma window incorporating a single channel analyser; for example, a window from approximately 620 to 700 keV may be used as a window for the 661 keV ^{137}Cs radionuclide. Such

instrumentation typically has inherent background levels due to electronic noise and naturally occurring radioactive material and cosmic radiation. The magnitude and variability of the background will determine the ability of the measurement to quantify concentrations relative to derived remediation criteria. However, it may still be possible to locate areas of contamination with some confidence; for instance, the gross gamma count rate for a standard 75 mm × 75 mm NaI scintillation detector gives a gross gamma background count rate of approximately 250 cps on a grassy field but approximately 750 cps in the presence of a uniform ^{137}Cs contamination at a level of 0.4 Bq/g.

Much larger NaI scintillation scanning systems used in aerial or vehicle mounted gamma spectrometry enable rapid detailed sophisticated processing of spectra to qualitatively and quantitatively detect the major natural gamma emitters of the thorium and uranium series, and ^{40}K, as well as prominent artificial radionuclides such as ^{137}Cs and ^{60}Co over large areas. However, the spatial resolution is comparatively poor.

In situ gamma spectrometry provides radionuclide specific measurements for gamma emitters (Fig. 15). There are limitations which must be accounted for in using this method, including the depth of the contaminant in soil, the homogeneity of the contamination, and background levels of the radionuclides of concern.

FIG. 15. Fixed location in situ measurements with a gamma spectroscopy instrument.

This monitoring technique is finding increasing applications in decommissioning monitoring and most manufacturers of NaI and high resolution detector systems offer portable equipment for this purpose.

4.3.1.3. Monitoring of underground structures and buried radioactivity

The final remediation monitoring plan may specify the monitoring of underground structures for potential contamination following remediation, if present at the site. Generally, subsurface areas of known contamination are not sampled directly. However, indirect monitoring of known subsurface contaminated areas can be achieved through the down gradient monitoring of subsurface water, and perhaps surface water, flora and fauna, and other appropriate pathway monitoring.

Many sites with contaminated land may have had building and underground structures associated with them from previous operations. These may include underground storage tanks, drains, regions where material had been excavated and filled with new material, and regions where additional soil has been stacked over the land to reduce surface exposure, e.g. in the land surrounding the Chernobyl nuclear power plant. Such instances are addressed in planning the remediation processes and in the development of the derived remediation criteria. Historical records of the site and existing knowledge from current or former workers provide an important information source of such buried structure and radioactivity.

It may be necessary to use physical measurement techniques to identify buried structures or disturbed ground following remediation and subsequent environmental restoration (Fig. 16). These techniques may include ground penetrating radar and electromagnetic detection systems for drains, etc.

Intrusive radiation measurement techniques may also be considered as part of the monitoring process for underground structures and areas where elevated contamination is not expected. For example, monitors fitted to cables or rods may be used to monitor drains, and sensors may be lowered down vertical holes or shafts in pipes or chases that have been remediated or are not expected to be contaminated. Underground tanks or drains are generally removed or filled with an inert substance, such as concrete following remediation. A potential difficulty is estimating the MDA of such a system for the radionuclide of concern.

Consideration of waste management requirements are necessary if the remediation plan proposes to fill and leave contaminated abandoned lines or tanks. The radiological criteria for these structures and monitoring approach may be different than for other aspects of the remediation.

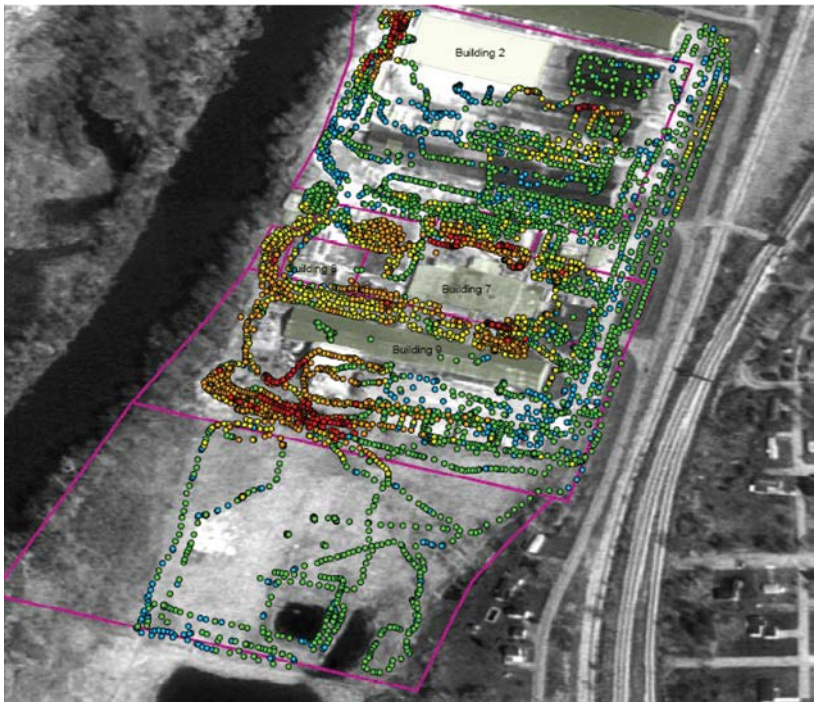

FIG. 16. Gross gamma survey using GPS coordinated logging [17].

4.3.2. Sampling of water and sediments

The sampling of water and sediments is often a necessary prerequisite in the determination of radionuclide migration. Contaminants in solution on suspended particulates and absorbed into sediments could be transported by water. Lateral movement could be highlighted by analysing surface water, water from a system of survey boreholes and bottom sediment samples. Downward radionuclide migration through the vertical soil profile can be determined in core samples and groundwater samples. Sampling approaches are outlined, for example, in Ref. [30].

Samples may be collected from lakes and other surface water by dipping, scooping or suctioning water. Care must be taken to ensure that the sample will be representative of the body of water of interest. It is necessary to avoid disturbing bottom sediments; sediments inadvertently collected with the water sample are immediately filtered.

Groundwater samples are obtained from wells drilled into the aquifer. It is important that the well installation is engineered so that samples will be representative. It is also important to cap the monitoring wells with locked plates

so that contaminants cannot be intentionally or inadvertently introduced into the aquifer. Monitoring wells into aquifers are usually removed from service and filled with an inert material such as bentonite clay as soon as practical after the required information has been obtained from them. This activity is typically coordinated with the environmental protection regulatory body.

Sediment samples of 500–1000 g are typically sufficient, while water samples may require 2–8 L, depending on the radionuclides of interest and the required analytical sensitivity.

4.3.3. Air monitoring

Air monitoring is not typically performed in final remediation monitoring because of the inaccuracies in the specific location of the source of radioactivity. Rather, the inhalation pathway may have to be considered in the development of remediation criteria. An exception is air monitoring for radon emanation from sites with radium or possibly thorium contamination where clearly defined exhalation rates are established, usually given as becquerels per square metre. In these cases, a given area, normally 1 m^2, is monitored for radon. If air monitoring is to be performed for other reasons, potential airborne contamination can be evaluated by collecting a sample of the air and analysing the sample for the contaminants of interest. Sample collection techniques depend on the physical and chemical nature of the contaminant. Potentially contaminated sample media are generally collected by passing a known volume of air through filters which capture airborne particles, whereas gaseous contaminants may be collected by chemical water scrubbing, freezing traps or oxygenic traps. The collected samples are then analysed in a laboratory. Care must be taken with the assessment of radon progeny and reference made to established techniques for conducting such measurements.

Methods commonly used for the sampling and analysis of radon include track-etch devices and air sampling through filter papers or charcoal packs, followed by gross beta or gamma counting to detect radon and its radioactive decay products. Air monitoring may be performed for certain radionuclides by use of a detector that continuously monitors the filter. In other cases, it may be possible to directly monitor radioactive gases with a flow through ionization chamber.

4.3.4. Monitoring of flora and fauna

Some species of flora and fauna have the ability to concentrate naturally occurring or artificial radionuclides. Iodine, for example, is known to concentrate

in certain algae and shellfish, while plants such as lichens, heather, fir and spruce, as well as mushrooms and tea may concentrate isotopes of caesium.

As some flora and fauna can move through the environment, it may be difficult to identify and collect representative samples. Samples and sampling methods are determined on a case specific basis, depending on contaminants and pathways of interest. Consideration needs to be given to species including bacteria and other small organisms that may be able to mobilize contamination, especially for areas that have been classified for restricted release.

Normally, flora and fauna are monitored as a consideration of the environmental protection programme. These may also be monitored as part of the verification programme. Flora monitoring may be required, for example, if the remediation technique includes use of certain plants to selectively extract low levels of contaminants from shallow soil [31].

A sampling and analysis programme that supports final remediation monitoring requires a plan that includes specifications for analysis, validation techniques, verification and management of samples, and reporting monitoring results. Examples of requirements for the special quality plan can be found in MARLAP [20].

4.3.5. Sampling site media

Certain radionuclides cannot be effectively measured directly in the field. Samples of the medium under investigation (e.g. soil, water) are collected and subsequently analysed with a laboratory based procedure. On the simplest level, this includes the analysis of a smear sample using a gross alpha–beta counter. More involved analyses include gamma spectrometry, beta analysis using liquid scintillation counting, or alpha spectrometry following separation chemistry.

As with direct measurements, a sample must be representative of the media of interest if the results are to be useful in making judgements and decisions regarding compliance with criteria. It is also imperative that the sampling method provide a sufficient quantity of sample to assure the required measurement sensitivities for the radionuclides of concern. When developing the sample collection procedures, it should be considered that the sample may have to be divided into multiple aliquots for different analyses to be performed.

4.3.5.1. Soil and surfaces

Soil samples and surface wipes are normally used in monitoring for compliance with clearance or remediation criteria because these categories typically have established criteria. Sampling other media, which might include

contamination migration and potential exposure pathways, may provide supplementary information to complete the site profile.

The design of specific plans may be developed to address the following sampling considerations:

— Sample devices (e.g. trowel, hand auger, soil core sampler, submersible water pump, high volume air filter, etc.).
— Sample preparation equipment (e.g. weighing scales, volume measuring devices, soil screening sieves, water filtering equipment, etc.).
— Sample containers, e.g. container material (glass, plastic, cloth, container size).
— Sample preservation equipment and agents (e.g. refrigeration, ice, formaldehyde or acid additives).
— Personnel protective gear (e.g. respiratory protective devices, protective clothing, such as gloves and booties, life preservers, etc.). It should be noted that insecticides and other personal protective chemicals may interfere with some analyses, especially if chemical contaminants are also present.
— Sample labels and identification systems.
— Chain of custody forms and procedures.
— Shipment containers and packing materials that comply with regulations.
— Shipment forms.
— Analysis request form identifying the type of radioanalysis to be performed, and any special instructions.

Such information is available in procedures developed by numerous radiological and environmental agencies (see Ref. [32]).

Samples of soil from the surface (0–15 cm) may provide measurements of contamination that was deposited on the surface by air, water or other pathways. Surface samples are also used to determine whether remedial actions are sufficient, by measuring the level of residual contamination at an excavation surface. A common method of sampling surface soil is by hand auger, 5–10 cm in diameter. A small shovel or trowel may also be used. However, greater care is needed to maintain a uniform sized sample when sampling in this manner. Depending on the contaminants of interest and the analytical method used to achieve the required measurement sensitivity, a soil sample of 500–1000 g is usually sufficient.

4.3.5.2. Subsurface soil sampling

Sampling of subsurface soil may be necessary if there is a potential for buried radioactive material or migration of contamination beneath the surface.

However, subsurface soil sampling is typically conducted during the characterization phase rather than for monitoring following remediation. An exception would occur when a dismantled building had leaks or spills that migrated into the soil beneath the building, so that it was impractical to sample during the characterization phase. Several techniques that are typically used for subsurface sampling include coning, cone potentiometer testing and trenching (Fig. 17 and Table 5).

4.3.5.3. Underground structures

Underground structures include underground storage tanks and vaults, lines and pipes, and facilities which may be built underground for security reasons. Underground structures typically have elevated moisture, increased radon and more fauna (animals, insects, etc.) than surface structures. Therefore, monitoring subsurface structures presents additional challenges (Fig. 18). For structures that are large enough for human occupancy, portable lighting and portable ventilation units are important to facilitate monitoring. Entry into smaller structures large enough for human entry, such as tanks, pipes and lines, must be carefully controlled to minimize risk to the workers. Monitoring smaller structures, such as pipelines, etc., can be achieved by remote means. Crawlers fitted with sodium iodide detectors or Geiger–Mueller (GM) detectors with logging capability have been used to some extent (Fig. 19). However, in many cases, it may be necessary to excavate some of the lines and take samples for analysis. Sampling at specified

FIG. 17. Example of trenching to monitor a large subsurface area for potential contamination [17].

TABLE 5. SOIL SAMPLING EQUIPMENT [33]

Equipment	Application	Advantages/disadvantages
Tier	Soft surface soil	Inexpensive; easy to use and decontaminated; difficult to use in stone or dry soil
Scoop or trowel	Soft surface soil	Inexpensive; easy to use and decontaminated; trowels with painted surfaces need to be avoided
Bulb planter	Soft soil, 0–15 cm	Easy to use and decontaminated; uniform diameter and sample volume; preserves soil core; limited depth capability; can be difficult to decontaminate
Soil coring device	Soft soil, 0–60 cm	Relatively easy to use; preserves soil core; limited depth capability; can be difficult to decontaminate
Thin-wall tube sampler	Soft soil, 0–3 m	Easy to use; preserves soil core; easy to decontaminate; can be difficult to remove cores
Split spoon sampler	Soft soil, to bedrock	Excellent depth range; preserves soil core; tube may be used for shipping core to lab; may be used in conjunction with drill rig for obtaining deep cores
Shelby tube sampler	Soft soil, to bedrock	Excellent depth range; preserves soil core; tube may be used for shipping core to lab; may be used in conjunction with drill rig for obtaining deep core
Bucket auger	Soft soil, 7.5 cm–3 m	Easy to use; good depth range; uniform diameter and sample volume; may disrupt and mix soil horizons greater than 15 cm
Hand-operated power auger	Soil, 15 cm–4.5 m	Good depth range; generally used in conjunction with bucket auger; destroys soil core; requires two or more operators; can be difficult to decontaminate

intervals may provide adequate evidence that the lines meet established remediation criteria. However, care must be taken to find the location of low spots, and to ensure that sampling includes these areas (see Fig. 18).

FIG. 18. Example of a potentially contaminated large underground line [17].

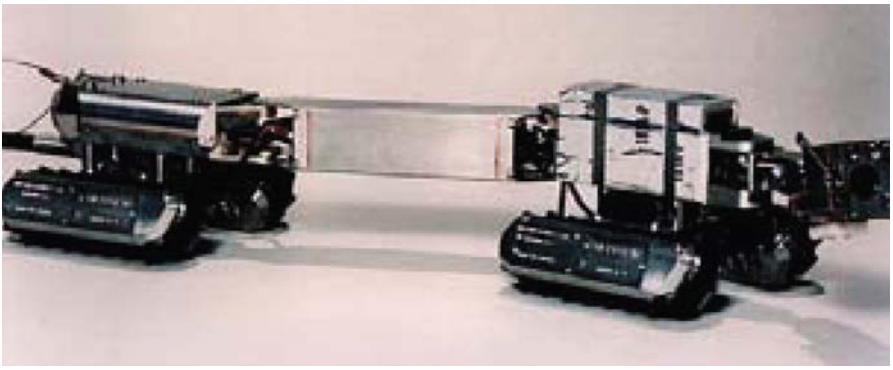

FIG. 19. Example of a pipeline crawler [34].

4.3.5.4. Buildings

Sampling of building materials may present challenges to the workers (Fig. 20). For example, during the operation of a facility, a worker may be accustomed to working in the vicinity of sources and contamination. However, workers probably have not had much experience sampling paint or floor tiles, for example. Therefore, specific sample types must be determined early in the planning for final remediation monitoring, and procedures developed to ensure

FIG. 20. Example of a building undergoing remediation. Final remediation monitoring will have to consider how to sample the subfloor, walls and ceiling of this laboratory [17].

that the sample is taken in a representative manner, enough sample is collected to meet analytical needs, and that it is not contaminated with unwanted materials. Sampling of building materials may include cores of ceilings, walls and floors. Building drains may need to be monitored. Floors under tiles or linoleum may be contaminated from spills which were cleaned on the surface but may have soaked under the floor coverings. This is particularly possible for alpha contaminants.

If unencapsulated materials were handled or spilled during the life of the facility, then additional sampling is warranted to confirm that contamination is not present. This sampling may occur during the characterization but if any airborne radioactivity is generated during remediation, then additional checks are necessary during final remediation monitoring. Conduit and lines throughout the building are sampled during the final remediation monitoring. Ventilation ducts, etc. are monitored during the characterization, including exhaust and supply ducts. Again, the criteria established for the final remediation monitoring will dictate whether the characterization survey results are adequate to determine compliance with the remediation criteria. Cracks, crevices and joints in controlled areas during operation need to be particularly inspected. Surface monitoring may not reveal contamination at depth. Adequate planning and implementation of the characterization can reduce the time and cost of the final remediation monitoring.

4.3.6. Removable surface activity for buildings and structures

The amount of surface activity that is removable is typically determined by wiping ('smearing') the surface with an absorbent cloth or paper using moderate pressure. The purpose of a smear is to detect the fraction of contaminant that could be removed from incidental contact.

Although criteria for removable contamination have been developed by many countries, the collection process is not strictly quantifiable.

A gross count or radionuclide specific analysis is then performed on the smear. The general convention is to wipe an area of approximately 100 cm^2 although this may be adjusted, depending on the amount of material on the surface. If the swipe is much larger than 100 cm^2, the wipe will not be able to collect it adequately and the measurement will, therefore, not be representative. Swipe samples are usually not taken of soil, in dusty areas or on surfaces with known contamination. Self-absorption of swipe samples may be a concern for smears that will be counted by direct methods for removable alpha contamination. However, swipe samples can be dissolved and processed in accordance with radiochemistry procedures if necessary.

4.3.7. Sample collection and preservation

A valid sample is vital to the quality of the measurement. A sample which is not representative of the medium under investigation may provide high quality but misleading information. It is essential that the analytical laboratory be involved in the development of the sampling programme during the planning for final remediation monitoring. A sample which has not been correctly preserved and processed may corrupt the measurement. Samples must be collected, preserved and stored to prevent any significant change in the concentration and form of the radionuclides present. Specific requirements may be documented in a plan for sampling and analysis.

Some considerations during collection include:

— Concrete samples for tritium analysis must not be heated while coring. Similarly, they must not be exposed to cooling water. When they are analysed, only the inside of the core needs to be used.
— Water samples collected for radon must be stored in well sealed containers. It is difficult to keep radon, a noble gas, contained.
— Samples collected for tritium analysis need to be wrapped, stored in airtight containers and preferably frozen.

— Acidification will prevent the loss of actinides onto container walls but will promote the loss of volatile species, such as iodine isotopes.
— The addition of carriers to the solution can be useful to limit adsorption onto the container walls.
— Soil samples are particularly prone to cross-contamination, particularly if small diameter cores are used and there is a strong concentration gradient with depth. Samplers specifically designed for radioactivity determination need to be used. Cores need to be removed, preferably without pushing them out of the sampler end. The use of a split spoon is one technique for accomplishing this sampling task (see Table 5).

4.3.8. Sample preparation

The sample preparation process is normally designed to convert the sample into a form that can be analysed by a specific method and may improve the limit of detection or uncertainty. The laboratory needs to discuss these methods with the customer to ensure that they will not corrupt the measurement or produce misleading information. Methods include:

— Removal of flints and other impervious rocks from soil: This concentrates the active fraction of the sample.
— Homogenization: Where a large sample is needed to ensure a representative activity concentration, it is frequently homogenized so that representative smaller masses can be removed for each analysis. This is particularly important when collecting samples for development of the radionuclide vector.
— Drying and ashing: Drying removes the water content to remove the effects of variable water content on the sample results but will remove tritium. Ashing will remove unwanted organic material but will also remove volatile species, such as iodine, polonium, ^{14}C and ^{137}Cs.
— Dissolution is used as a step in the chemical process to support the analytical procedure or to concentrate certain radionuclides.

4.3.8.1. Sample sizes

Sample sizes depend on the specified chemical processes that will be employed (Table 6) in accordance with the sampling and analysis plan or other

TABLE 6. TYPICAL RADIOCHEMICAL CAPABILITIES

		Solid samples		Liquid samples	
Group	Radionuclides	Minimum mass to achieve MDA (g)	MDA (Bq/g)	Minimum mass to achieve MDA (g)	MDA (Bq/kg)
1	Most gamma emitters	100–1000	0.1	500–4000	0.5
2	Gross alpha and beta	5	0.1–1	500	0.1
3	H-3, C-14, Pu-241	10	0.1	50–4000	5 to 10
4	I-129	50	0.05	50	50
5	Fe-55, Ni-63, Tc-99	5	0.1	100	1
6	Sr-90	5	0.01	5	1
7	Po-210	10	0.02	200	0.05
8	Pu-238, Pu-239, Pu-240, Pu-230, Pu-232, Am-241	5	0.02	200	0.05
9	U-234, U-235, U-236, U-238, Pu-242	5	0.02	200	0.05
10	Np-237	5	0.01	200	0.05
11	Ra-226	5	0.05	100	0.01

document that reflects the sample preparation protocol. Considerations in determining the size of sample to collect include:

— The analyses required;
— The limits of detection required;
— The heterogeneity of the medium being sampled;
— Whether some of the sample is to be retained for possible audit or in case of failure of analysis.

Many laboratories offer a range of detection capabilities which are tied to sample size, sample pretreatment, type analysis (counting instrument) and counting time. The cost per analysis is directly related to the required MDA.

4.3.9. Sample handling

The handling of samples (see Fig. 21) is an important activity where specific attention needs to be paid to:

— Loss of volatile radionuclides, such as the evaporation of tritiated water or loss of radon gas;
— Loss of radionuclides, such as tritium and ^{14}C from biological degradation;
— Changes in the physical and chemical form of the radionuclides, such as precipitation from solution;
— Adsorption of the radionuclide onto the container walls.

FIG. 21. Monitoring of soil coring taken during final remediation monitoring [17].

4.3.10. Laboratory analysis

An example of standard methods for radiochemical analyses of water samples can be found in Refs [35, 36].

In all except the simplest of remediation exercises, sampling followed by radiochemistry is an important part of the process. Only radiochemical methods have the capacity to produce specific answers for pure alpha and beta emitters at low levels. The subject is large and only the basic information is provided:

— Gamma spectrometry: This technique follows the same process described earlier. Generally, only a limited degree of sample preparation is involved. Problems can involve the escape of radon from radium contaminated samples. This leads to low values of ^{214}Bi and ^{214}Pb, which are the main gamma emitters in the chain, and are generally used to estimate ^{226}Ra activity. Samples to be analysed for ^{226}Ra by gamma spectroscopy need to be sealed and stored approximately three weeks prior to counting. Generally, laboratories will add in a correction for loss of equilibrium as a consequence of the residual radon escape. Other problems can arise from radionuclides with very close gamma emissions, for example ^{235}U at 185 keV and ^{226}Ra at 186 keV. Where both are present, other less effective, gamma lines are used to provide individual activities, and in some cases, peak summation techniques are applied to derive a concentration from a combined peak. These techniques introduce greater uncertainty into the analytical result.
— Alpha spectrometry: Chemical separation is used to concentrate the element of interest and remove interfering radionuclides. Alpha spectrometry is typically used for analysis of plutonium isotopes, ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{242}Pu, or thorium isotopes, ^{228}Th, ^{230}Th and ^{232}Th. Once the isotopes are extracted, they are plated onto a thin disc. This is then placed in front of a thin window, large area, silicon diode detector in a vacuum chamber. These detectors have extremely low backgrounds and generally good energy resolution. However, there is enough overlap of energies that radiochemical separation is required. As chemical recovery can vary from sample to sample, it is customary for the laboratory to use an internal standard to estimate recovery. Although it is preferred to use an isotope that is not present in the sample as an internal standard, that is not always possible. In cases like this, split samples are used with an internal standard applied to one of the split samples. This increases the uncertainty in the measurement.
— Beta counting: For beta emitters, counting usually involves isolating the element of interest followed by counting using a GM or proportional counter in a heavy shield. Beta spectroscopy by liquid scintillation is

typically used in the analysis of specific low energy beta emitters, such as ^{63}Ni, ^{14}C, ^{241}Pu and ^{3}H. When ^{241}Pu is counted this way, the results may require correction for the presence of other plutonium isotopes.

— Tritium: For solid materials, the most satisfactory approach is complete chemical or thermal decomposition to produce a tritiated water sample which can be counted by liquid scintillation techniques. In some cases, tritium can be leached from a solid sample. This works for samples with surface tritium contamination but not for samples where the tritium has diffused in depth. Distillation can be used to separate tritium oxide from samples including water, vegetation and some biological material, but does not work where the tritium is bound to stable organic molecules. Oil samples containing tritium can be analysed by liquid scintillation but interferences from chemical and photoluminescence is common. Correction for these interferences impacts on the detection sensitivity of the measurement.

— Laboratory gross alpha and beta measurements: These measurements are effective for a large number of samples because they are quick and cheap (Table 7). However, because laboratories can differ in the calibration radionuclide used, both for alpha and beta emitters, and because there is a range of detectors employed which can have different energy responses, results from laboratory to laboratory may differ, perhaps significantly. In order to avoid misleading measurements or difficult to compare results from laboratory to laboratory, a precise methodology (calibration, energy windows, etc.) has to be well established, otherwise identical samples can have different results quoted by different laboratories. This technique is often used for checking consistency of the radionuclide vector, where regular measurements are made of the gamma spectrometry/gross alpha/gross beta ratios.

— Non-radiometric techniques: These are typically based on mass spectrometry and are useful for certain long half-life radionuclides. This is because 1 Bq of a long half-life radionuclide is represented by a large number of atoms. For example, 1 Bq of ^{238}U has a mass of 0.1 mg and can be detected. Non-radiometric analyses become attractive for alpha emitters with a half-life in excess of approximately 2×10^6 a. Generally, such equipment is used for geophysical research at natural activity levels and such laboratories will not process samples with potential activities much above background.

— ICP–mass spectrometry (ICP–MS): This technique is one of the most versatile and sensitive atomic spectroscopy techniques available. It can be used to determine the concentrations of over seventy elements. The detection limit of the technique extends to the parts per billion range in soils

TABLE 7. TYPICAL MEASUREMENT SENSITIVITIES FOR LABORATORY RADIOMETRIC PROCEDURES

Sample type	Radionuclides or radiation measured	Procedure	Approximate measurement sensitivity
Smears (filter paper)	Gross alpha	Gas-flow proportional counter; 5 min count	5 dpm
	Gross beta		20 dpm
		Alpha scintillation detector with scaler; 5 min count	10 dpm
		Gas-flow proportional counter; 5 min count	80 dpm
		End window GM with scaler; 5 min count (unshielded detector)	30 dpm
		Liquid scintillation spectrometer; 5 min count	
	Low energy beta (H-3, C-14, Ni-63)		0.1 Bq/g
Solid materia	Cs-137; Co-60; Ra-225 (Bi-214)[a]; Th-232 (Ac-228); U-235	Germanium detector (25% relative efficiency) with multichannel analyser; pulse height analyser; 500 g sample; 15 min analysis	0.1 Bq/g
	U-234, U-235, U-238; Pu-238, Pu-239, Pu-240; Th-227, Th-228, Th-230, Th-232; other alpha emitters	Alpha spectroscopy with multichannel analyser; pyrosulphate fusion and solvent extraction; surface barrier detector; pulse height analyser; 1 g sample; 16 h count	0.02 Bq/g

TABLE 7. TYPICAL MEASUREMENT SENSITIVITIES FOR LABORATORY RADIOMETRIC PROCEDURES (cont.)

Sample type	Radionuclides or radiation measured	Procedure	Approximate measurement sensitivity
Water	Gross alpha	Gas-flow proportional counter; 100 mL sample; 20 min count	0.04 Bq/L
	Gross beta	Gas-flow proportional counter; 100 mL sample; 20 min count	0.04 Bq/L
	Cs-137; Co-60; Ra-226 (Bi-214); Th-232 (Ac-228); U-235	Germanium detector (25% relative efficiency) with multichannel analyser; pulse height analyser; 3.5 L sample; 16 h count	0.04 Bq/L
	U-234, U-235, U-238; Pu-238, Pu-239, Pu-240; Th-227, Th-228, Th-230, Th-232; other alpha emitters	Alpha spectroscopy with multichannel analyser — solvent extraction; surface barrier detector; pulse height analyser; 100 ml sample; 30 min count	0.5 Bq/L
	H-3	Liquid scintillation spectrometry; 5 mL sample; 30 min count	10 Bq/L

[a] Indicates that a member of the decay series is measured to determine the activity level of the parent radionuclide of primary interest.

and to the parts per trillion range in water. This sensitivity makes ICP–MS an attractive complement to decay-counting techniques in the radiochemical analysis laboratory. For very long lived radioisotopes (e.g. ^{244}Pu, ^{99}Tc, ^{129}I), ICP–MS may be faster and more sensitive than decay counting [37]. In addition, sample preparation for ICP–MS can avoid some of the analyte separation and purification steps required for decay counting, providing an additional dimension of time savings. Another important feature of ICP–MS is its ability to provide isotopic distribution information (e.g. ^{238}U versus ^{235}U). This information is frequently useful in determining the age and/or origin of materials. The isotopic discrimination capabilities of ICP–MS make possible the calibration technique known as isotope dilution. In this procedure, a sample is analysed for one isotope after having been spiked with a different isotope of the same element (e.g. analysis of ^{235}U might involve spiking with ^{233}U). The spiked sample is carried through all preparation and analysis steps; in this way, any matrix or procedural effects that might influence the ^{235}U signal will influence the ^{234}U signal to precisely the same extent. Final quantization relies on measuring the ratio of the unknown (here the ^{235}U signal) to the known (^{234}U) signal. Isotope dilution is a way of generating highly precise and accurate data from a mass spectrometer and has been used in the characterization of many certified reference materials.

For more sophisticated measurements, at substantially higher cost, ICP–MS with magnetic sector, instead of quadrupole, detection can be applied. Sector instruments are capable of resolving species of very similar mass. For example, ^{99}Tc might be resolved from a contamination of ^{99}Ru with a high resolution mass spectrometric detector. More typically, high resolution instruments are employed for their higher signal to noise ratio and, therefore, superior detection limits. A single collector high resolution ICP–MS can be purchased for roughly twice the cost of a quadrupole ICP–MS. These instruments, as most analytical equipment, can be expected to require about 2–10% of their purchase costs in annual maintenance costs. For example, thermal ionization mass spectroscopy (TIMS) relies on thermal ionization from a heated filament rather than plasma to generate the ions that are subsequently analysed. Although more precise measurements can be obtained than by quadropole ICP–MS, TIMS requires substantially more delicate operator involvement, leading to markedly reduced sample throughput.

Time of flight plasma mass spectrometers have recently appeared on the market; they have not yet built up a historical record of performance that would permit reliable comparison with ICP–MS equipment. Likewise,

Fourier transform mass spectrometers are in the research phase and are not considered practical options for routine radiochemical analysis at this time.

— Laser application: Lasers can be used to excite uranium [38] and lanthanide complexes in solution. During or following excitation, the complex relaxes to a lower energy state by emitting photons of light that can be detected. The amount of light produced is proportional to the uranium or lanthanide element concentration. The light emitted can be detected by fluorescence or phosphorescence. With fluorescence and phosphorescence, the detector is at right angles to laser excitation. Fluorescence light is emitted simultaneous to the excitation.
— Phosphorescence detection: This differs from fluorescence in that the emitted light is not simultaneous to the excitation. This enables the light source to be pulsed and the measurement to occur when the laser source is off, which improves the signal to noise ratio over fluorescence. The sample is illuminated by a laser, which is then turned off. Light then phosphoresces, or decays, from the sample of organic material with a relatively short lifetime. The sample can be irradiated a number of times, or pulsed, each with subsequent counting of the phosphorescence decay. A pulsed nitrogen dye laser can be used as the source. Other lasers can also be used. Chloride ion and other ions may cause interference and, if present, need to be removed before measurement.
— Kinetic phosphorimetry: This measures the rate of decay of the uranium or lanthanide element complex signal. Measurements are taken at fixed time intervals. In aqueous solution, the uranium or the lanthanide element is complexed to reduce quenching and increase the lifetime of the complex.
— Other techniques: These may include neutron activation analysis, X ray fluorescence and other techniques. In certain instances, such as analysis of stable metal tritides, it may be appropriate to use scanning electron microscopy to measure the concentration of the metal, and then infer the tritium concentration. Before an analytical technique is specified, careful consideration of detection limits, turnaround time, cost and acceptance by the regulatory body and other interested parties must be considered.

4.3.11. Transfer and chain of custody

Samples need to be accompanied by an approved chain of custody record (see Appendix XI). The chain of custody establishes responsibility by individual at a specified time. This chain of custody may be used for legal as well as administrative purposes. The chain of custody will normally include the following information:

— A unique sample code;
— Date and time of sample collection;
— Details of any specific hazards or unusual aspects of the sample;
— Analyses required;
— Preservation procedures applied;
— Customer name and contact details;
— Contract or charging number.

The chain of custody is provided by the person who collects the sample. The person who receives the sample signs the chain of custody and provides a copy to the person who provided the sample, much like a receipt. Each subsequent transfer of the sample will generate a new signature from the individual who receives the sample.

5. ANALYSIS AND INTERPRETATION OF SURVEY RESULTS

Section 5 deals with analysis and interpretation of measurement results from land, buildings and structures. The methods usually applied to make these analyses are essentially the same although the relevant criteria discussed in Section 2 might be different.

Measurements, even in the correct quantity, have to be interpreted and the operator needs to describe how this was done in the final remediation monitoring report. For example, in many measurements, the background is subtracted to determine the concentration. A convenient approach is to express the results as the fraction of the relevant derived remediation criteria. If these are tabulated along with some measure of the uncertainty in the value, it makes it easy to see which areas have very low levels and those which are closer to, or exceed, the remediation criteria. It will then be possible to find out what the operator did about high levels and the results after further remediation is performed.

Data assessment consists of three processes: data verification, data validation and data quality assessment [39]. Data assessment is performed prior to the use of the data to determine whether the site meets the remediation criteria. An example of a process of assessment of results is presented in Fig. 22 [20].

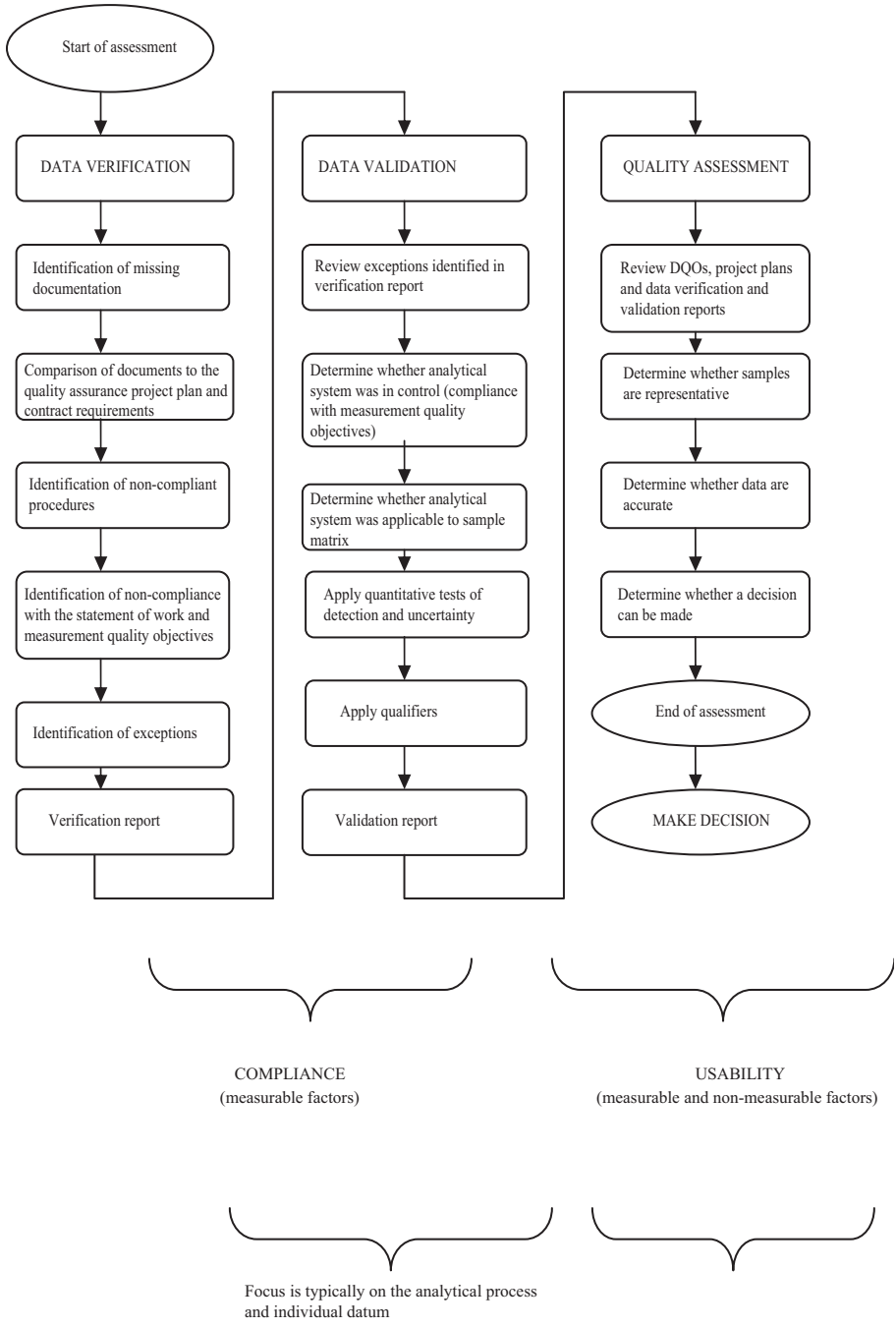

FIG. 22. Example of a process of assessment of results [20].

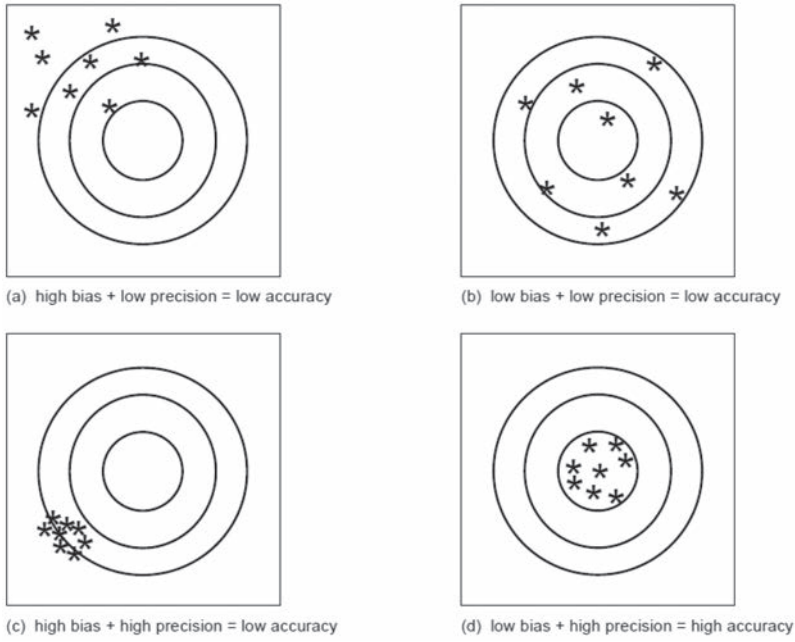

FIG. 23. Measurement bias and random measurement uncertainty [9].

5.1. DATA QUALITY INDICATORS

Data usability is achieved through data quality indicators. The data quality indicators include precision, bias, representativeness, comparability, completeness and accuracy. Precision and bias are considered to be quantitative measures of data quality. Comparability and representativeness are considered to be qualitative measures, and completeness includes both qualitative and quantitative measures. Accuracy is based on both data bias and precision, which are quantitative measures (Fig. 23).

5.1.1. Precision

Precision is determined when a measurement is repeated by an individual with the same instrument using the same procedure a number of times. This precision can be compared to different individuals using the same instrument and procedure to perform the same measurement. The instruments can then be varied, etc. until the precision of the process is determined. This is then considered in the error estimates for performing measurements of the same type. Default values for

use in the determination of precision measurements are documented in Ref. [40]. Methods to determine estimates of precision for specific laboratory analyses are found in MARSSIM [9] and MARLAP [20].

5.1.2. Bias

Bias is a variation in a measurement that occurs with preponderance. Bias is not random and is not compensated by statistical approaches. Bias is determined through assessments. For laboratory measurements, spiked samples, trip blanks, laboratory blanks and other QC checks provide indications of bias. Control charts provide a necessary means of ensuring instrument quality and identification of bias. For field measurements, bias can be determined by collecting samples for radiochemical analysis at locations where direct measurements have been made. A potential problem with this approach is ensuring that the sample is representative of the measurement.

One particular (bias) problem that can occur is the use of averaging routines for surface gamma measurements. Many geographical information systems have the capacity to smooth results over a series of points. It is normal procedure for land analysis but is important in both land and building cases that the smoothing takes place over an area which is smaller than the defined averaging area, otherwise small areas with unacceptable contamination levels may be missed. These systems also have the capacity to produce colour contour maps which aid presentation of the results. In the same way, it is important that there is a clear colour change between areas which clearly meet the criteria, areas which are just acceptable, areas which just fail and areas which are significantly over the limit.

5.1.3. Accuracy

Accuracy considers the combination of systematic (bias) and random (precision) uncertainty in the measurements. Accurate measurements have high precision and low bias. If measurements are determined to be inaccurate, it may be possible to use the data. For example, if the measurement is determined to be biased high, but all of the measurements are below the derived remediation criteria, it may be acceptable to use the data. Nevertheless, the identification of the bias is documented, along with how it was fixed and steps to prevent recurrence. The issue is discussed with the regulatory body.

5.1.4. Representativeness

Representativeness is a measure of the degree to which data accurately and precisely represent a characteristic of a population parameter at a sampling point

or for a process condition or environmental condition. Representativeness is a qualitative term that has to be evaluated to determine whether in situ and other measurements are made and physical samples collected in such a manner that the resulting data appropriately reflect the media and contamination measured or studied. Representativeness of data is critical to data usability assessments. The results of the environmental radiological survey will be biased to the degree that the data do not reflect the radionuclides and concentrations present at the site. Non-representative radionuclide identification may result in false negatives. Non-representative estimates of concentrations may be higher or lower than the true concentration. With few exceptions, non-representative measurements are only resolved by additional measurements. Representativeness is primarily a planning concern. The solution to enhancing representativeness is in the design of the survey plan. Representativeness is determined by examining the survey plan. It is common when monitoring includes both scanning and static measurements that static readings will be biased high and not representative because static measurements are typically directed at the highest scan measurement within a survey grid. For laboratory analyses, analytical data quality affects representativeness since data of low quality, typically associated with low activity samples, may be rejected for use in the data assessment.

5.1.5. Comparability

Comparability is the qualitative term that expresses the confidence that two data sets can contribute to a common analysis and interpolation. Comparability has to be carefully evaluated to establish whether two data sets can be considered equivalent in regard to the measurement of a specific variable or groups of variables. Comparability is an important qualitative data indicator for analytical assessment and when considering the combination of data sets from different analyses for the same radionuclides.

5.1.6. Completeness

Completeness is a measure of the amount of valid data obtained from the measurement system, expressed as a percentage of the number of valid measurements that should have been collected (i.e. measurements that were planned to be collected). Completeness is not intended to be a measure of representativeness; that is, it does not describe how closely the measured results reflect the actual concentration or distribution of the contaminant in the media being measured. A project could produce 100% data completeness (i.e. all planned measurements were actually performed and found to be valid) but the results may not be representative of the actual contaminant concentration.

Completeness can have an effect on the statistical evaluation. Lack of completeness may require reconsideration of the limits for decision error rates because insufficient completeness will decrease the power of the statistical tests by changing the estimated standard deviation of the measurements. Lack of completeness typically occurs when analytical data do not meet quality standards established for verification and validation, and are subsequently flagged with a data qualifier, a QC indicator that the data may not be usable (see Section 5.4.2).

5.2. COMPILATION OF DATA

The data collected during the monitoring for compliance can take various forms, including, for example:

— The sample grid for a particular survey unit;
— The gross count rate of a proportional counter;
— The daily instrument functional checks on a field instrument;
— The spectrum of a collimated in situ spectrometer;
— The printout of a liquid scintillation counter or a mass spectrometer situated in an external laboratory;
— Integrated gamma measurements recorded by a GPS based detection system carried across the site, based upon a random or specified grid pattern.

Whatever the type of measurement system, the resulting data have to be compiled into an appropriate overall data management system for the project. The establishment and design of the system need to reflect the quality management practices as described in Section 3. Data that are entered into the data management system must be complete to be useful. Of critical importance is a time and location corresponding to each monitoring result, whether from a field instrument or from laboratory analysis. The time and location may refer back to a sketch or map of the area. If so, the map needs to have a date and be initialled by the person who generated it. Locations of monitoring points are numbered and referenced to the data results.

Results from special samples and measurements, and results of investigations need to be integrated into the databank in a manner that permits their retrieval and use to support the remediation recommendation.

5.3. DATA CONVERSION

The calculation and documentation of measured activities from raw data need to be in a form that can be easily compared to the derived remediation criteria for the project, which are established during the planning phase. These criteria may be expressed in terms of exposure (μSv/h), the specific activity of a key radionuclide to be remediated (Bq/g), contamination levels (Bq/cm² or dpm/cm^2), total activity concentrations (Bq/g) or total inventory (Bq). As noted in Section 4, some instruments read directly in the quantity of interest; however, this is not always the case. Conversions may be required and are routinely achieved through the application of calculations within the database of collected information. These calculations account for the various instrument specific factors (e.g. instrument efficiency, energy response and dependence, physical probe area, effective probe area, etc.). It is necessary to check the logic and arithmetic behind these calculations and ensure that they are formally documented, reviewed and approved. Similarly, hand calculations or spreadsheet calculations are checked and maintained through the document control system. For comparison of survey data to the criteria, the survey data from field and laboratory measurements must be converted to the same dimensional units as the remediation criteria. For example, in the case of measurements of surface activity, it is important to account for the physical surface area assessed by the detector in order to make probe area corrections and to report data in the proper units (i.e. Bq/m^2, dpm/100 cm^2).

Some instruments have background counts associated with the operation of the instrument. A correction for instrument background can be included in the data conversion calculation. Analytical procedures, such as alpha and gamma spectrometry, are typically used to determine the radionuclide concentration in soil in units of becquerels per kilogram. Net counts are converted to derived remediation criteria units by dividing by the time, detector or counter efficiency, mass or volume of the sample, and by the fractional recovery or yield of the chemistry procedure (if applicable). Instruments, such as portable ionization chambers or micro-R metres, used to measure exposure rate, typically read directly in millisieverts per hour. However, some large scale gamma scintillation detectors provide data in counts per minute or counts per second which require conversion to millisieverts per hour based upon use of site specific calibration factors developed for the specific instrument configuration. In addition, in situ gamma spectrometry data may also require special analysis routines before the spectral data can be converted to soil concentration units or exposure rates.

5.4. DATA ASSESSMENT

Data assessment tasks are generally completed off-site after the results of field or direct measurements and the documentation of laboratory analyses have been collected for defined portions of the site or, in some instances, for the entire site. The process of sampling and interpretation is iterative during the remediation effort, with the results of one sampling effort perhaps indicating the need for further sampling in specific well defined areas to locate sources of contamination or to define areas that exceed derived remediation criteria. Data interpretation seeks to ensure that the conclusions derived from the results of the monitoring are consistent with the final remediation monitoring plan and demonstrate compliance with the remediation criteria [41].

The results of most data interpretation are not quantitative and the conclusions are mainly drawn on the basis of the weight of evidence that supports the conclusions. In many cases, a number of supporting tests or analyses may be required and, as such, qualitative conclusions are based on a combination of the analyses [42].

5.4.1. Data verification

Following its integration into the data management system, the first step in the basic data assessment process involves the review of the raw data to provide assurance that the data have adequate quality to support the decision regarding the adequacy of the remediation effort.

During the planning of the final remediation monitoring, certain data requirements were identified and documented. The primary source of the data requirements was the derived remediation criteria. Data verification is performed to ensure that the data that are collected during the remediation monitoring are of sufficient quality to meet the requirements specified in the remediation plan. It is at this point that it becomes obvious that an insufficient plan will produce data for which it will be difficult to demonstrate that they meet the criteria. Data verification includes checks for consistency. Data that are transferred from one medium to another may interject errors; verification is performed to identify transcription errors.

The basic review process includes an overall review of legibility and accuracy of field generated documents and electronically recorded data. Factors such as scan coverage, number and type of measurements or samples, and survey locations need to be confirmed. Selection and use of appropriate instrumentation and analytical methods need to be in accordance with the overall monitoring plan details for the project as described in Section 3. Calibration, performance tests and other QC records need to be verified as having been conducted. Overall

conformance of the collected information with the original survey plan and implementing procedures need to be confirmed, and any deviations must be documented and any impact on data quality assessed and reported. Sample analysis results need to be reviewed for their compliance with analytical specifications and quality requirements, and a portion of the calculations needs to be independently verified.

Data verification is also performed to ensure completeness of the data. For example, a field measurement that includes the measurement value, dimensional units and location but does not include the date/time of the measurement is not useful.

Analytical data that have too high associated errors are typically assigned a data qualifier by the laboratory (see Section 5.4.2). If that data qualifier is missing, the data may adversely affect the decision that this data set represents.

Data verification is performed through audits, QC checks, surveillance and self-audits, technical reviews and inspections. Included in these evaluations is the quality support documentation, such as control charts, etc., that clearly provide assurance that the measurements meet the project requirements as stated in the quality management programme.

When these data are judged to meet the stated quality requirements, a verification report is generated and maintained in the file. It includes a list of data that have been reviewed, by what criteria and annotates corrective actions taken. Verification reports are typically annotated on a checklist that is included in the project quality management programme.

5.4.2. Data validation

Data validation criteria are established early in the planning phase. Data validation provides a check to ensure that the data are technically feasible. An air sample that is reported in becquerels per gram would be an obvious error that would be identified by data validation. Statistical quantities (e.g. standard deviation, mean) derived from monitoring results have to be determined and calculated in order to compare with design assumptions. To ensure that adequate data were obtained (see Section 3), it is usually necessary to perform data conversion before validation of the data.

Once the verification report is completed, the data validation process begins. Although portions of the data verification and data validation process can be accomplished in parallel, there is an additional burden for effective communications between the groups as the concurrent reviews proceed.

Qualified data are any data that have been modified or adjusted as part of statistical or mathematical evaluation, data validation or data verification operations [43]. Data may be qualified or rejected as a result of data validation or

data verification activities (Table 8). Data qualifier codes or flags are often used to identify data that have been qualified. Although there is no standard list of data qualifiers, a project specific scheme can be established and fully explained in the quality management programme. The following are examples of data qualifier codes or flags derived from qualifiers assigned to results in the United States Environmental Protection Agency Contract Laboratory Programme [44, 45].

Inconsistent data need to be separated out from the main database of information for more detailed examination. This follow-up examination may lead to acceptance or rejection of the data based upon quality requirements. Rejected data are not discarded. They are retained and an explanation as to why they are not included in the decision making process is kept with the data. Normally, a data qualifier is assigned to these data as part of the data validation process.

TABLE 8. EXAMPLES OF DATA QUALIFIERS

Qualifier (flag)	Qualifier description
U or <MDC	The radionuclide of interest was analysed for, but the radionuclide concentration was below the minimum detectable concentration (MDC). The actual result of the analysis needs to be reported so that this qualifier would inform the data evaluator that the result reported is also below the MDC.
J	The associated value reported is a modified, adjusted or estimated quantity. This qualifier might be used to identify results based on key radionuclide measurements or gross activity measurements (e.g. gross alpha, gross beta). The implication of this qualifier is that the estimate may be inaccurate or imprecise which might mean that the result is inappropriate for the statistical evaluation of the results. Key radionuclide measurements associated with radionuclide vectors that are not inaccurate or imprecise may or may not be associated with this qualifier. It is recommended that the potential uncertainties associated with surrogate or gross measurements be quantified and included with the results.
R	The associated value reported is unusable. The result is rejected due to serious analytical deficiencies or QC results, usually based on the data verification process. These data would be rejected because they do not meet the data quality objectives of the survey.
O	The associated value reported was determined to be an outlier. If data are assigned an O qualifier or flag, an explanation needs to be included with the data. Data with an O qualifier or flag are usually rejected.

5.4.3. Data quality assessment

Data quality assessment is a process that confirms that the data collected have sufficient quality that from a statistical and scientific perspective there will be enough data of adequate quality to meet the remediation project goals. The focus is on data usability, which again is documented in the final remediation monitoring plan.

The data assessment process examines the data in the context of:

— Existing validated data from previous monitoring work;
— Known or established patterns of contamination associated with the project site or area;
— Established linkages to known sources of contamination;
— Previously established relationships between other chemical or biological contaminants known to exist on the site (i.e. contaminant radionuclide vector).

In many areas where spot contaminants are a concern, more than one contaminant is often involved (i.e. combination of radioactive species and heavy metals). Previous data interpretation work may have established relationships between different contaminants that exist on-site. Use of correlation statistics among the different contaminants can be used to assess the quality or acceptability of the data. Similarly, correlations between contaminants and physical characteristics of the material can also be used as a screening tool to assess the quality of the data (e.g. pH, grain size, colour, odour, etc.) in soils and sediments.

5.5. GRAPHICAL DISPLAY OF RESULTS

In general, it is often easier to interpret collected data in graphs or maps than in tabulated data. Three common approaches for data interpretation are:

— Plots drawing the spatial distribution of activity;
— Scatter plots, e.g. comparing two different parameters;
— Histograms of the density distribution of measured activity values.

To display the spatial distribution of data, many simple spreadsheet programmes support 2-D or 3-D plots (e.g. EXCEL, SURFER) and these can provide a useful overview of the radiological information about the site. For the land distribution review, a posting plot is a useful tool for visually portraying the

data that may be plotted directly onto survey unit maps or displayed graphically, such as in histograms, or contour mapped onto a suitable computer spreadsheet or geographical information system (GIS) software package. An example of a posting plot and a frequency plot is presented in Figs 24 and 25.

The posting plot is a simple graphical representation of the values of the monitoring data spatially arranged. A quick review of the plot can discern areas with elevated values or identify trends that may otherwise be missed. For example, from a posting plot, it may be observed that although all of the measurements are less than the derived criteria of 100 (arbitrary units), there may be a trend towards the survey unit boundary of continued higher readings. This would prompt further investigation outside the boundary (see the data on the left portion of Example (b) in Fig. 24).

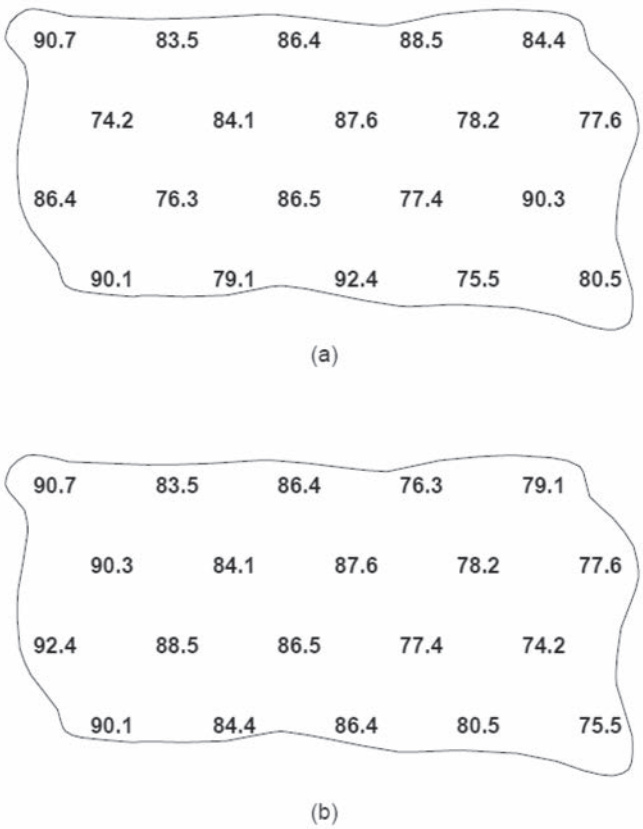

FIG. 24. Example posting plot [9].

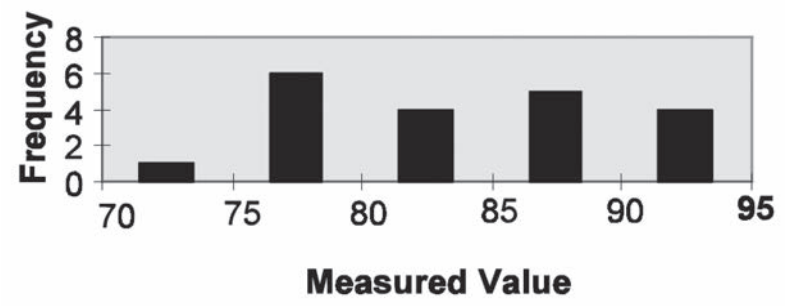

FIG. 25. Example frequency plot [9].

A frequency plot is a useful tool to quickly determine whether the data are 'well behaved'. For example, looking at the frequency plot in Fig. 25, there is a slight indication of a bimodal distribution in the data between 75 and 80, and between 85 and 90. If the remediation criterion was, for example, 100, it is questionable whether these data would support release of the site without additional sampling, since it would be expected that, based on this distribution, there would be some analytical results between 95 and 100. The true test is in the statistical analysis but a simple screening approach may save the time and expense to run more sophisticated analyses.

Scatter plots are useful presentation tools to show the relationship between two types of measurements. In the example shown in Fig. 26, two different methods were used for measuring the concentration of radium contamination at a site. The first measurement involved a gross gamma measurement at the site, assuming 70% equilibrium of radon with its gamma emitting daughters ^{214}Bi and ^{214}Pb.

The second measurement was performed by high resolution gamma ray spectrometry analysis of samples taken at the site. The specific isotope measured was ^{214}Bi.

A comparison of the two sets of measurements shows a clear correlation and would, thus, support the gross gamma field measurement as a valid measurement technique.

A histogram is simply a special type of bar graph in which the categories are intervals. The intervals need to be of equal distance concerning the assumed distribution of the values. In the case shown in Fig. 27, a log-normal distribution was assumed. Using too few or too many categories may not adequately show the distribution of the data.

The data depicted in Fig. 27 are derived from the same data pool as the Method 1-named data in the scatter plot described in Fig. 26. Although using the same data, this type of diagram provides a different kind of information.

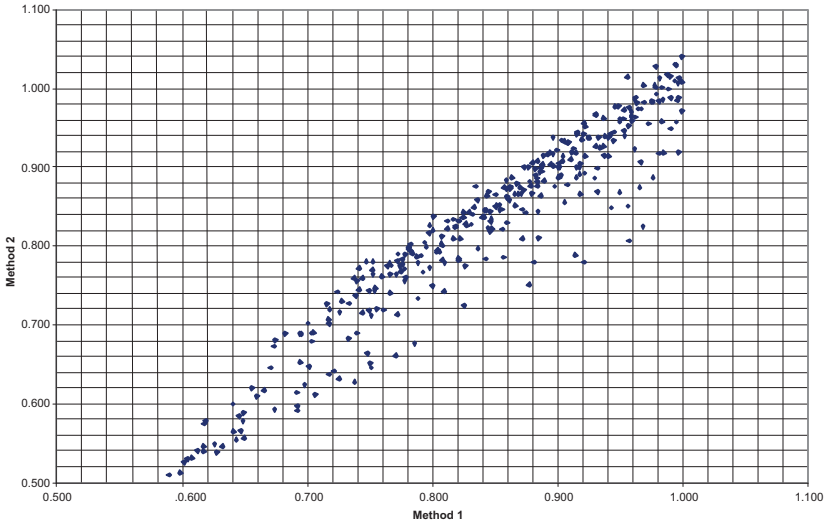

FIG. 26. Scatter plot.

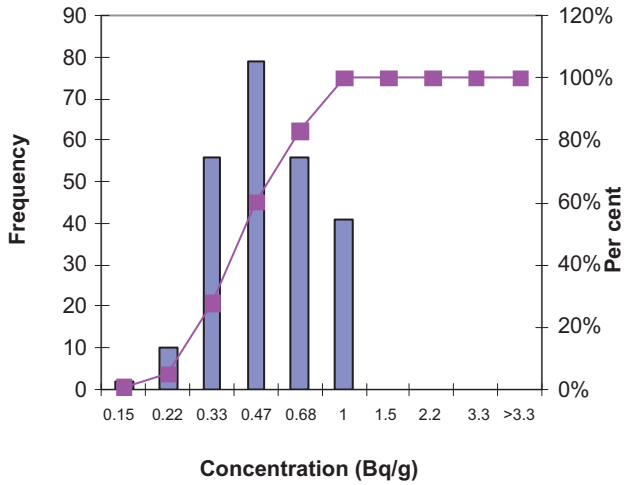

FIG. 27. Histogram of collected data.

In addition to the description of an entire sample with a few numbers, e.g. means, standard deviation and medians, the frequency distribution gives a good overview of the accordance of the data sample with the distribution assumed in the design phase (Fig. 27). In Fig. 27, areas with values larger than one have undergone decontamination and, therefore, are not present in the diagram.

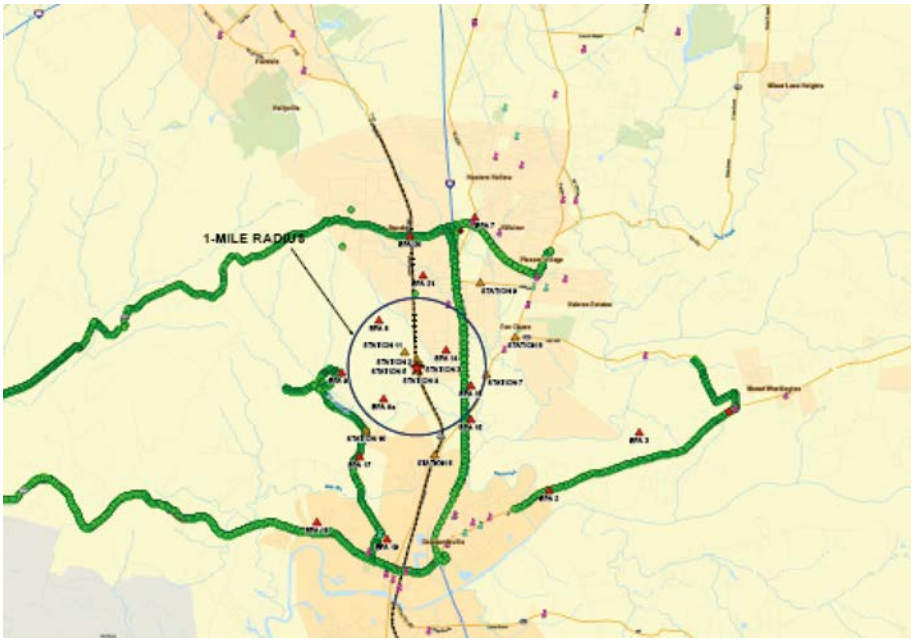

FIG. 28. Technical data collected in combination with GPS data and plotted on an area map [17].

The introduction of GPS and GIS technologies has revolutionized the process of the mapping of land. Previously, land areas had to be marked out with a grid — typically with a spacing of 1 m^2 — and each area individually surveyed, and the result recorded and subsequently transferred to a data system for analysis. GPS technology now enables a sensor reading, its position and the time of the measurement to be electronically recorded into a data logger. These data can then be downloaded into a computer database and then processed using a suitable GIS programme to produce detailed contour maps depicting regions of similar radioactivity.

Figure 28 presents an example of such a GPS/GIS plot. Each green dot represents a reading from a sensor. The database includes the value of the reading, a northing and easting, and the time that the reading was collected. The data can then be graphically plotted on a map of the area. This type of measurement is particularly useful for measurements taken in an open area outside but is of limited use indoors. Interference of the GPS signal from trees, atmospheric conditions, buildings, etc. can limit the use of this technology.

5.6. UNCERTAINTIES

5.6.1. Identification of uncertainties

The next step in the data assessment process involves the determination that any uncertainties associated with the collection, processing or interpretation of the data are clearly identified. A variety of methods can be selected to address this phase of work, including statistical analyses, data visualization with charts and graphs, and uncertainty identification. Data usability is achieved through data quality indicators, as discussed in Section 5.1. These include:

— Identification of the precision of the data collected;
— Determination of the bias in the data set;
— Using the precision and bias to determine the accuracy of the data set (see Fig. 23);
— Checks on the completeness of the data set;
— Review of the representativeness of the data;
— Review of the comparability of data.

Each evaluation of each data point by the data quality indicators has the potential to identify, quantify or otherwise affect the uncertainty of a measurement or group of measurements. The effects of precision and bias on uncertainty were discussed in Section 5.1.

Completeness of the data set can be regarded as the collection of the required number of measurements or sample analyses that is necessary to meet the project objectives. Data that are included from other sources or excluded from consideration during the data assessment process affect the overall uncertainty of the data set. The representativeness of the data is the degree to which data accurately and precisely represent the concentrations of the constituents or the characteristics of the material. The comparability of data is defined as the degree of confidence with which one data set can be compared to another. The requirements that define the applicability of comparability directly affect the uncertainty associated with the data that may be included in the data set.

The accuracy and reproducibility of the quantification process can be regarded as the fundamental principles supporting the quality of data. Measurements need to be made in a sufficient number and manner so as to provide a statistically acceptable definition of the degree of confidence. This requires the use of consistent and documented methods throughout the data collection process.

A number of different statistical techniques are suitable for analysis of collected data. Such statistical techniques are needed to determine whether the data are of the right type, quality and quantity to support the decision of compliance with criteria. Some of these statistical techniques are described in the Bibliography. Monitoring points are compared and, where suitable data are available, differences in means can be tested using statistical tests. Since in most studies the data distribution is seldom normal, statistical analysis will usually require either data transformation or non-parametric statistical tests. Another statistical technique is multivariate analysis that can be used to relate variables among a large number of monitoring points. This technique is usually used to group data that are similar on the basis of the test variables selected. Advanced statistical testing methods may be introduced into the process of assessing all data available if the test is fully documented and evidence is provided that the test is appropriate for the data set. Additional information on statistical tests can be found, for example, in Refs [15, 46, 47].

5.6.2. Precision and systematic uncertainties (bias)

Precision is a measure of agreement among repeated measurements. As repeated measurements taken under the same conditions may be higher or lower than previous measurements, it is appropriate to discuss precision in statistical terms. Systematic errors, also called bias, accumulate during the measurement process and result from faults in sampling designs and procedures, analytical procedures, sample contamination, losses, interactions with containers, deterioration, inaccurate instrument calibration and other sources. Bias causes the mean value of the sample data to be consistently higher or lower than the true mean value. Bias cannot be addressed through statistical evaluation of the data set. Laboratories typically utilize QC samples to assess possible bias. In simple terms, spikes, repeated measurements and blanks are used to assess bias, precision and contamination, respectively. The laboratory clients typically submit known blanks, spiked samples and references as samples within a group of samples to provide an independent check on the laboratory's programme, and are effective in evaluating the precision and bias of analytical processes.

Fieldwork, using scanning or direct measurements, eliminates some sources of error because samples are not removed, containerized or transported to another location for analysis. The worker's technique or field instrument, however, is another source of bias. In this case, detecting bias might incorporate field replicates by having a second worker to revisit measurement locations and following the same procedure with the same instrument as was used by the first worker. This is an approach used to assess precision of measurements. A field instrument's calibration can also be verified by functional checks by one or more

workers during the course of a survey and recorded on a control chart. Differences in the set-up or use of instruments by different workers may reveal a significant source of bias that is quite different from sources of bias associated with laboratory work.

The following factors need to be considered when evaluating sources of bias, error and uncertainty. Contamination is an added factor to consider for each of the following items:

— Sample collection methods;
— Handling and preparation of samples;
— Homogenization and aliquots of laboratory samples;
— Field methods for sampling, scanning or direct measurements;
— Laboratory analytical process;
— Use, control and handling of background samples, check sources and calibration standards of field personnel and laboratories;
— Total bias contributed by all sources.

The magnitude of the measurement system variability needs to be evaluated to determine whether the variability approaches or exceeds the true but unknown variability in the population of interest. Errors, bias or data variability may accumulate to the point of rendering data unusable for achieving survey objectives. Systematic investigations of field or laboratory processes can be initiated to assess and identify the extent of errors, bias and data variability, and to determine whether the DQOs are achieved. An important aspect of each QC determination is the representative nature of a sample or measurement. If additional samples or measurements are not taken according to the appropriate method, the resulting QC information will be invalid or unusable. For example, if an inadequate amount of sample is collected, the laboratory analytical procedure may not provide a quantifiable result. The QC sample must represent the sample population being studied. It is often difficult to generate a representative spiked sample of known concentration for specific environmental media.

5.6.3. Treating uncertainty

Uncertainty can be dealt with by regularly reviewing the characteristics of the material encountered as the monitoring proceeds. As the remediation project progresses, more information on the characteristics of the material will become available. Monitoring techniques need to be designed so that changes in material characteristics can be easily identified and documented as the project progresses. Monitoring techniques also need to be amenable to change (through a formal process) as required in reaction to a better understanding of the material

characteristics. Some consideration must also be given if a particular detector response changes with different material characteristics, e.g. the difference in a gamma spectrum as a function of the material density. This variation in material characteristics must also be taken into account when calculating activity concentrations. Monitoring techniques need to be sufficiently flexible to be able to handle some degree of variation in material characteristics.

Counting errors are often not the limiting factor in the repeatability or accuracy of results. The following sources of uncertainty need to be considered:

— Distribution of the contaminant within the survey unit;
— Seasonal deviation of radiological monitoring response (depending on temperature, groundwater level, snow covering, saturation of soil, presence of vegetation, etc.);
— Horizontal stratification of radioactivity concentration in soil because of both natural and anthropogenic causes;
— Fluctuation of the radionuclide vector.

All of these factors need to be assessed by the operator. In many cases, it is difficult to quantify these exactly and a 'best estimate' may have to be made. This needs to be supported by a documented, rational argument of the assumptions made to achieve the estimate in a document sometimes called a 'technical basis document'. Methods for uncertainty evaluation are described in Refs [20, 48]. Two examples of uncertainty estimates are presented below.

5.6.3.1. Gamma surface activity

Gamma surface activity is normally determined using large sodium iodide detectors. The net count rate from these is compared with the value predicted as corresponding to the maximum acceptable residual level for the area. A simplified form of the equation to estimate the uncertainties in this process and the magnitudes would be:

$$C = (S - BGe)/(NF \times OF \times DF \times LF \times FF) \quad (1)$$

where

C is calculated activity;
S is estimated gross count rate;
BGe is estimated background count rate;
NF is response factor derived for the nominal averaging volume in a particular defined geometry;

OF is influence of activity outside that defined geometry;
DF is influence of non-uniformity with depth throughout the measured volume;
LF is influence of lateral non-uniformity over the averaging volume;

and *FF* is radionuclide vector factor.

The uncertainties quoted in Tables 9 and 10 are derived from practical experience, and depend on the exact situation. The estimates are at the 95% level of confidence.

Combining these in the conventional manner results in an uncertainty on the order of 45%.

TABLE 9. UNCERTAINTIES FOR GAMMA ANALYSIS

Parameter	Cause of uncertainty	Uncertainty (%)
S	Statistical uncertainty.	10
BGe	Statistics of derivation process.	5
NF	Calculational uncertainties and/or non-uniformity in the test volume and radiochemical analysis limitations.	10
OF	Volumes outside the calculation volume will produce counts. There may have been some attempt in the derivation of NF to account for this, in which case the uncertainty is zero but moves, instead, to LF. Concentration with depth will not be uniform.	10
DF	The gradient may be a decrease in activity with depth or an increase or a peak somewhere within the volume.	25
LF	The gamma field may not be uniform over the surface of the monitoring volume, particularly where deposition is by particles, rather than from solution.	25
FF	This is important where the gamma measurement is being used to control a key radionuclide where other radionuclide vectors have comparable radiological significance. This could be the case for a mixture of fission products and actinides.	25

TABLE 10. UNCERTAINTIES FOR BETA ANALYSIS

Parameter	Cause of uncertainty	Uncertainty (%)
Estimate gross count rate (*S*)	Statistical uncertainty	20
Estimated background count rate (*BGe*)	Statistics of derivation process	5
Response factor derived for the nominal averaging area (*NF*)	Calculational uncertainties and/or non-uniformity in the test area and radiochemical analysis limitations	10
Influence of activity outside that defined area (*OF*)	Areas outside the calculation area will produce counts	5
Influence of potential screening by surface grease, etc. (*DF*)	Screening by grease	5
Influence of lateral non-uniformity (*LF*)	Non-uniformity over the area in question	10
Radionuclide vector factor (*FF*)	Some components will contribute little to the signal but may be radiologically important	10

5.6.3.2. Apparent beta surface contamination level

The technique above can be used to estimate the uncertainty associated with monitoring a high energy beta emitting radionuclide with a GM detector and ratemeter.

$$C = (S - BGe)/(NF \times OF \times DF \times LF \times FF) \quad (2)$$

where C is calculated activity.

The overall uncertainty is on the order of 25%.

It is useful to estimate uncertainties prior to collecting field measurements or samples. If the uncertainty is likely to have a major influence on the remediation programme, it needs to be recognized before measurements are taken. If the material has low contamination compared to the derived remediation criteria or is contaminated well above the criteria, the uncertainty is less significant. In such a case, the volume of soil removed, for example, is not largely influenced if the area is slightly over-remediated to make allowance for the uncertainty in the measurement.

6. DECISION ON COMPLIANCE WITH APPLICABLE CRITERIA

The overall objective of a remediation project is to conduct the appropriate amount of remediation to achieve compliance with the applicable criteria for the intended immediate or future use of the site. In the context of this objective, at final remediation monitoring, it is necessary to determine whether compliance with the applicable criteria has been achieved, based upon an evaluation of the data and information collected from the remediated site. The method of determining whether or not sample results exceed remediation criteria is important to the success of the remedial programme and, therefore, needs to be made in a consistent manner to demonstrate compliance with the remediation criteria.

If the evaluation of data with the applicable derived remediation criteria demonstrates compliance, the results are documented in such a manner that the specific area of compliance on the remediated site and the corroborating data can be directly linked. If the evaluation process does not demonstrate that the criteria have been adequately satisfied, further action is taken to identify and resolve the deficiencies. These follow-up actions can include re-examination of the site (or portions thereof), further review of previously collected information and data, additional remediation, collection and analysis of new samples collected from within the re-remediated area(s) of the site, and evaluation of the new data in accordance with the criteria established for the project.

This section provides guidance on the use of valid monitoring data and information to determine whether compliance with remediation criteria has been achieved.

6.1. COMPARISON WITH CRITERIA

The decision on compliance or non-compliance is based upon direct comparison between the data collected from the site following completion of the remedial work and the applicable derived remediation criteria from the final remediation monitoring plan described in Section 3. Compliance is based upon the mean of the sample results. Final remediation monitoring is designed and performed in a way that allows sufficient quantity and quality of data to provide a statistically defensible set of arguments that demonstrate compliance with the release criteria. The statistical evaluation provides a defensible basis for decision making regarding the radiological conditions of the survey unit, the entire site

and future actions towards site release. Criteria for release of buildings, structures and land can differ.

If the mean of the sample results for the area in question is less than the remediation criteria, then the remedial actions are considered to have been successful and no further work is necessary. However, if the mean of the data is close to the remediation criteria and the standard deviation of the data is comparatively large, it is prudent to statistically examine the data to provide assurance that the remediation effort has been successful.

If the mean of the sample results exceeds the remediation criteria, the remediation efforts were not successful and additional actions are necessary. These actions can include:

— Re-evaluation of the data and perhaps additional sampling;
— Further remediation efforts and subsequent resampling;
— Re-designation from release for unrestricted to restricted use.

In the case where the mean of the data is less than the remediation criteria but some of the data exceed the criteria, then the data are statistically evaluated and each sample that exceeds the remediation criteria is further evaluated to ensure that it does not exceed a threshold value. This could occur if, for example, a large number of samples were taken from a survey unit. If it is assumed that the results of only one sample analysis exceeded the remediation criteria, and the resulting mean were below the remediation criteria, and if this solitary sample result greatly exceeded the release criteria, it would be necessary to further evaluate that sample result to determine whether additional remediation were necessary in that area. Guidance on addressing such a situation can be found in section 5.5.2.6 of NUREG-1575 [9].

In addition, if some sample results are equal to or greater than the criteria, then statistical analyses are necessary. If these analyses fail, additional remedial work is required to achieve compliance.

For some remedial cleanup situations, several radionuclides may be present within the contaminant matrix. Although one radionuclide may dominate the overall mixture, it is necessary in the determination of compliance to recognize that the other radionuclides will contribute to the overall exposure calculation and must be accounted for in the final determination of compliance with the remediation criteria.

The particular radionuclides present, the nature of the contamination (i.e. surface activity or volumetric) and the methods used to evaluate the radiological conditions (e.g. direct measurements of gross activity, radionuclide specific analyses or use of surrogate measurements on soil samples) necessitate different approaches for developing appropriate criteria for implementing monitoring for

radionuclide mixtures. Appendix II describes the methods for determining remediation criteria if multiple contaminants are present. The underlying principle for multiple radioactive contaminants is the application of the unity rule, which means that the sum of the ratios of the individual radionuclide concentrations measured on the remediated site to their respective remediation criteria developed for the site must be equal to or less than one (a sum of the fractions mathematical operation). Thus, in considering this multiple contaminant situation, there is not a single remediation criterion but rather a group of criteria applicable to each radionuclide that has been identified to be part of the contaminant radionuclide vector for the site.

6.2. SURVEY UNITS VERSUS COMPLETE SITE APPLICATION

Following the completion of remedial activities, the assessment of the remediated site's compliance with the applicable cleanup criteria is often based on discrete sub-areas of the site rather than the entire site. The size of these survey units needs to be established at the outset of the project based upon the remediation objectives. This survey unit approach provides easier identification and more efficient follow-up remedial actions for failed areas on the site. However, the complete site can be released only if each survey unit complies with the remediation criteria.

The size of the survey units are normally determined by the expected contamination in the area and the location of the contamination — indoors or outdoors (see Section 3.5).

6.3. DECISION ON ABOVE CRITERIA LEVELS

Based on the specific exposure pathway model, some contamination in excess of the derived remediation criteria within a survey unit may be acceptable, provided that the average value for the site satisfies the criteria. This is particularly true for isolated small contamination (see Section 3). In such cases, additional considerations about the influence of any elevated levels have to be taken into account to demonstrate that the derived remediation criteria have been met.

Due to inherent statistical variation in the measurement process, there is a chance that a reading which is below the acceptance criterion is in fact from an area which is just above, and similarly a reading which is above the remediation criteria comes from an area which is below the remediation criteria. The approach

to uncertainty defined in the planning stage determines the acceptability of such results.

6.4. FOLLOW-UP ACTIONS FOR NON-COMPLIANT AREAS

There are several options if an area has been determined to exceed the remediation criteria. During the remediation process, it is often easier to further remove a small area of contamination that is close to the limit rather than risk failing the unit. If remediation is performed effectively, the fraction of the total site area close to the limit is likely to be small. If the remediation has been performed conservatively, then the fraction of the area close to the limit is small. However, if the remediation has been performed with less rigour due to time, personnel or budget limitations, then areas of the site may exceed the remediation criteria. The remediation monitoring approach is optimized to minimize the uncertainty for a given expenditure of resources. When the remediation is complete, the final remediation monitoring programme takes measurements and collects and analyses samples of predetermined survey units. It is expected that most survey units will meet the remediation criteria. One or more survey units may not meet the remediation criteria. Actions to address failed units have cost consequences. Follow-up actions that have cost implications in the event of a compliance failure are:

— Analysis of the reason for non-compliance with the derived remediation criteria;
— Review and confirmation of all data that led to the decision before undertaking any additional remediation or measurements;
— Additional measurements in accordance with the existing monitoring programme;
— Review of the design of the monitoring programme for conservatism;
— Revision of the remediation plan including additional remediation work;
— Reconsideration of end points from release for unrestricted to restricted use.

In the event that the follow-up actions are unable to yield compliance with the specified criteria, restrictions may be imposed on the site until a determination can be made by the site operator and regulatory body. In any case, changes to the remediation plan and additional remediation activities are clearly discussed in the final remediation report.

7. REPORTING OF MONITORING RESULTS

The results obtained from the monitoring programme and the subsequent conclusions drawn from the assessment of the results need to be presented in a stand-alone style document based upon a logical, traceable and consistent format. The final remediation monitoring report needs to be unambiguous and, as a minimum, provide an overview of the project's history, a description of the nature or 'radionuclide vector' of the contaminant(s) found on the site, the remedial cleanup strategy applied to address the contamination on the site, including the classification of areas within the site, the sampling protocols and instrumentation used in the monitoring programme, descriptive summaries of the field and analytical results obtained during the monitoring, the results of assessments conducted on the collected data, and the conclusions drawn from the data regarding the site's compliance with the remediation criteria. Sufficient information and data need to be provided in the final remediation monitoring report to allow an independent assessment of the results and substantiation of the conclusions drawn from the data. The report needs to comply with applicable regulatory requirements.

This section highlights key points to be considered during the preparation of the final remediation monitoring report.

7.1. PARTIAL SITE VERSUS COMPLETE SITE FINAL REPORTING

Depending on the approved monitoring programme, the results of this programme can be reported on a partial site basis as the remedial work proceeds or at the conclusion of the work when all of the remedial activities on the site have been completed. Completion of all final remediation monitoring and the final remediation monitoring report may considerably delay the final decision on release of the site. Decision on release of part of the site (particularly relevant for large areas) can be made on the basis of the release criteria derived for the whole site.

7.2. ELEMENTS OF THE FINAL REMEDIATION MONITORING REPORT

The final remediation monitoring report is developed as a comprehensive stand-alone document presenting the information necessary to demonstrate the site's compliance with the criteria established for the project. The report provides a logical review of the various programme elements and results used to arrive at

the decision regarding the site's compliance with the applicable remediation criteria. Key elements of the report include: details of the initiation of the project; a description of the site outlining its history and source of contamination, including the character of the contaminant 'radionuclide vector'; scaled maps or drawings depicting the layout and location(s) of the remediated area(s) prior to and following remediation; the remediation criteria to be achieved by the project based upon the characteristic 'radionuclide vector' associated with the contaminants and wastes found at the site; a list of materials that may have been left on the site, including location, concentration, persistence and migration potential; the strategy developed and applied to the site to achieve compliance; descriptions of the instrumentation and/or analytical methods used in conducting the monitoring and sample analyses; the data assessment process; data management, including conversion to the applicable derived remediation criteria units; a review of the monitoring results obtained and the QCs applied; the overall conclusions reached on the site's compliance with the applicable remediation criteria, including the results of any data evaluation using statistical methods to confirm compliance; a discussion of actions taken as a consequence of individual measurements or sample concentrations that may have exceeded the criteria levels established for the project reported together with follow-up data after subsequent additional remediation or monitoring performed to demonstrate that areas of the site that exceeded criteria were adequately resolved; an overview of any problems or events that were encountered during the monitoring for the compliance process; and lessons learned during the monitoring process that could be utilized for the improvement of future monitoring programmes.

Table 11 provides an example of the contents for a final remediation monitoring report. Appendix VI presents an example of a checklist for final remediation monitoring that could be used to confirm that the various reporting elements have been addressed by the monitoring programme.

The final remediation monitoring report for the regulatory body may be supplied with a non-technical summary. The intended audience for this non-technical summary is other interested parties, including the site owners, area residents, non-governmental organizations and prospective purchasers or users of the site.

7.3. RESOURCE MATERIALS FOR REPORT PREPARATION

Record keeping, documentation and data management are important activities that are conducted to substantiate the various aspects of the monitoring for the compliance process. These activities facilitate tracking of planned and achieved actions, monitoring points and areas of investigation, as well as sample

TABLE 11. EXAMPLE OF TABLE OF CONTENTS FOR THE FINAL REMEDIATION MONITORING REPORT

	Non-technical project summary
1.	Background project information
	1.1. Reason for remediation 1.2. Scope of monitoring activities 1.3. Acceptance criteria selected for demonstration of compliance (regulatory requirements, guidance, etc.)
2.	Site description
	2.1. Inventory and description of site 2.2. History of site 2.3. Type of contamination (e.g. radionuclides) 2.4. Classification of areas according to their original contamination 2.5. Selected reference areas
3.	Final remediation monitoring objectives
	3.1. Remediation criteria 3.2. Criteria for selection of samples versus direct measurements 3.3. Management of radioactive material
4.	Preparation of site for measurements
	4.1. Boundaries 4.2. Physical characteristics 4.3. Underground structures 4.4. Reference grid developed for the site
5.	Monitoring strategy and techniques
	5.1. Management approach 5.2. Compliance monitoring strategy 5.3. Monitoring instruments, capabilities and limitations, and techniques 5.4. Personnel qualifications 5.5. Survey units
6.	Sampling programme
	6.1. Determination of number of samples to be collected for each survey unit 6.2. Justification of the overall number of samples 6.3. Schematic of sample collection sites

TABLE 11. EXAMPLE OF TABLE OF CONTENTS FOR THE FINAL REMEDIATION MONITORING REPORT (cont.)

7.	Monitoring results
	7.1. Overview of monitoring results 7.2. Monitoring results for each survey unit: — The number of samples; — A map or drawing showing the reference system; — The measured sample concentration(s); — The statistical evaluation of the measured concentration; — Judgemental and miscellaneous sample data sets reported separately; — Discussion of anomalous data including areas with elevated direct radiation detected during scanning that exceeded the investigation level; — Statement on whether the survey unit satisfied the investigation level and whether the elevated measurement exceeded this level. 7.3. Comparison of monitoring results with the derived remediation criteria 7.4. Actual final disposition(s) of the material 7.5. Environmental monitoring and dosimetry results
8.	Quality control
	8.1. Uncertainties on measurements 8.2. Number of control measurements
9.	Lessons learned
	9.1. Major malfunctions and other unexpected occurrences 9.2. Significant changes during monitoring made to the final status monitoring from what was proposed in the monitoring/remediation plan 9.3. Suggestions for future improvement
10.	Conclusion on site compliance with remediation/site release criteria
	10.1. Residual activity left on the site (if any implications for final site status) 10.2. Conclusions drawn from monitoring data 10.3. Operator's recommendation regarding site status 10.4. Certification by property operator
11.	References
12.	Appendices (site drawings and maps, data tables, etc.)

analyses and technical results that establish the basis for decisions made on achievement of compliance with the applicable remediation criteria. Record keeping, documentation and management of important information pertaining to

the planning, performance of monitoring, compilation and assessment of results, and decision making are essential for the independent or regulatory review of the monitoring strategy and results.

Different types of documentation (e.g. protocols, reports) can be used during the monitoring programme to address the requirements of the approved quality management programme. The records generally fall into three main groups:

(a) Field records: field instrument test records, field measurement records, sampling tracking/management records (chain of custody), QC measurement records, field procedures, deficiency and problem identification reports, corrective action reports.
(b) Laboratory records: laboratory measurement results and sample data, sample tracking/management records (chain of custody), test methods and procedures, QA procedures, deficiency and problem identification reports, corrective action reports.
(c) Data handling/management records: compilation of field and laboratory results, assessment and data verification checklists, final remediation monitoring report, etc.

The field and laboratory records are the primary sources of analytical information to be incorporated into the final monitoring report. They need to be supplemented by references to the project's work plan that outlines the original scope of work for the project.

An effective means to organize records in an easily retrievable system is to determine what records will be needed during the remediation monitoring, develop standard forms for each application, and publish a schedule of when the forms will be used. It is then rather easy to check to see that the proper forms are generated and filed at the appropriate frequency. Standard forms provide the added benefit of being easily audited.

8. VERIFICATION SURVEY

The regulatory body will decide whether the site has been remediated to a satisfactory level. The regulatory body may take a series of measurements to confirm the results from the final remediation monitoring. It may not be necessary to monitor the site completely, depending on the initial site

characterization information, particularly if the initial characterization showed that much of the site met the remediation criteria without any work being performed. If the regulatory body generally has confidence in this information, only very limited confirmation monitoring is usually necessary. If the operator has an approved QA programme, the regulatory body can minimize the confirmation monitoring requirements, and expedite its evaluation of the final remediation monitoring.

Generally, it is more time effective for the regulatory body to review in greater detail those areas where significant work has taken place. The regulatory body may elect to concentrate on areas where measurements were made and recorded manually, and where the monitoring task was difficult, for reasons of poor access, poor working conditions or high background levels.

It is possible that the other interested parties will make recommendations to the regulatory body on the use of verification surveys. Keeping other interested parties involved as the work progresses allows them to be familiar with the activities and results.

Appendix I

PRACTICAL EXAMPLE OF THE DEVELOPMENT OF THE MONITORING STRATEGY

I.1. DEFINITION OF THE SITE TO BE MONITORED FOLLOWING REMEDIATION

I.1.1. Information from the historical site assessment

A facility, built in 1955, manufactured ^{63}Ni sources for use in gas chromatographs and other analytical instruments. The operation, which was not licensed, made approximately fifty sources per week, each with an activity of a few megabecquerels. The company received $NiCl_2$ solution, and plated the solution on various foils of different sizes, typically a few square centimetres, in a glovebox. The plated foils were then rinsed, and removed to a fume hood for final sizing. The foils were counted in a gas proportional counter and then packaged for shipping. The facility terminated operations in 1973 when the owner died unexpectedly. The building sat vacant during the intervening years. An urban renewal project wants to acquire this building and property as well as others in the area to build a commercial project (Fig. 29).

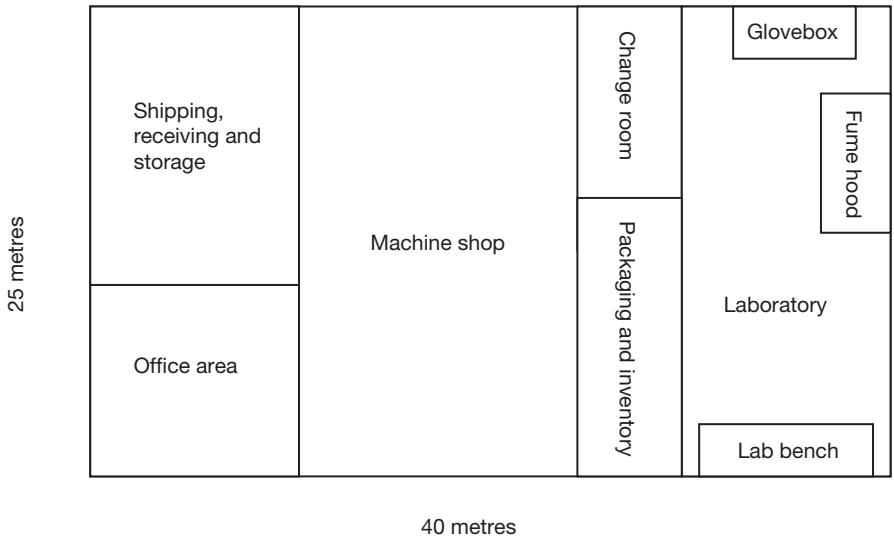

FIG. 29. Sketch of the ^{63}Ni processing facility.

Office: The office was used for sales, accounting and QA. No sources were allowed in the office area unless ready for shipping.

Shipping, receiving and storage: This area was used for receiving packages of ^{63}Ni solution. It also received other supplies and equipment necessary for production. It also stored packaged product while awaiting shipment, and stored packaged waste awaiting transport. The area provided warehouse shelves for storage of supplies and equipment. No unsealed sources were stored or used in this area.

Machine shop: This area was used for preparation of foils and for repair of equipment. It prepared packaged sources for transport into approved shipping containers. Instruments that had been returned for repair, such as gas chromatographs, were repaired in this room. No unsealed sources or materials were used in this area.

Change room: This room was used for lockers and shower facilities for laboratory personnel. It also provided routine entry/exit from the laboratory.

Packaging and inventory: This area was used as a passbox to the laboratory, entry to the change room and the machine shop. It received plated sources in plastic containers from the lab. It also received waste packaged in plastic bags from the laboratory. Counting equipment included a proportional counter and, later, a liquid scintillation counter. QA inspections were performed in this room. Sources were packaged into secondary containers and stored here until ready for shipment to the customer. Waste was placed in drums and stored until ready for pick-up for disposal.

Laboratory: The laboratory was used for preparation of ^{63}Ni plating solutions and plated foils in the glovebox. Plated foils were transferred to the fume hood for rinsing and polishing. Polished sources were counted on a proportional counter in the laboratory. Qualified sources were then placed on the laboratory bench for final assembly into source holders. The source holders were placed in plastic containers and transferred to the packaging and inventory area. Liquid wastes from the laboratory were transferred to a holding tank buried outside the building. Solutions were recovered from the tank and evaporated and exhausted through a filtered stack that serviced the glovebox and fume hood. The waste tank and feed lines had leaked over the years, and the subsurface soils had been contaminated.

I.1.2. Extracted information from the characterization

Samples were collected from the roof in the vicinity of the exhaust stack. No contamination above detectable limits (0.05 Bq/g) was identified in the roof materials. Ten soil samples were collected, primarily in the downwind direction up to 1 km from the site and confirmed that ^{63}Ni was not present in soil samples

above the MDA of 0.04 Bq/g. The sanitary and storm drain lines were verified by camera to be free flowing with no deposits built up along the path to the main drain. The facility storm water sump was opened, and the floor of the manhole and lines were allowed to dry. Direct measurements taken in the manhole on the floor and walls, and in the lines indicated no ^{63}Ni measurements above detection limits, estimated to be 38 Bq/cm^2, although radon progeny were present. The storm water drains empty into a main drain that emptied into a small retention pond approximately 2 km from the site. Two small fish were caught and analysed for ^{63}Ni. The sample results were less than the detection limit, estimated to be 0.85 Bq/g.

Ten measurements in the office area, focused on main aisles, indicated no readings above the MDA, estimated to be 24 Bq/cm^2. The office area was declared to be non-impacted, so it could be used during the final remediation and final remediation monitoring for office work.

Some samples were analysed for other radionuclides. It was determined that no other radionuclides were present except for naturally occurring radionuclides in background concentrations. No radionuclide vector was established.

Remediation activities described in the remediation plan were developed based on results from the characterization survey. Activities included removing the glovebox, fume hood and laboratory bench, and floor tiles in the laboratory. The underground lines and tank were removed, and surrounding soils removed and packaged as waste.

From these considerations, it was determined that the final remediation monitoring strategy would include the following:

— Based on the characterization survey results, no other isotopes were identified that are associated with this operation, so no radionuclide vector is necessary.
— Surface measurements on clean, flat, dry surfaces using a gas proportional detector connected to a monitoring instrument used in both scanning and scalar modes.
— Radiochemistry analysis of samples of floors and walls where surfaces were rough following remediation.
— Collection and radiochemical analysis of soil samples in the vicinity of the remediated underground tank and transfer lines.
— Collection and radiochemical analysis of water samples from the wash water collection tank.
— Characterization samples demonstrated that post-remediation air sampling is not necessary.
— The office area is determined to be non-impacted, so no monitoring will be performed in this area as part of this project.

I.1.3. Remediation criteria

The operator, in consultation with the regulatory body and other interested parties, decided that based on the future use of the site, release for unrestricted use was the preferred option. The regulatory body established a remediation goal of 300 μSv to critical members of the population, which based on the future use of the site, was conservatively estimated to be a child in a day care centre. The derived criteria for ^{63}Ni were 100 Bq/g in soil and surface activity levels of 100 Bq/cm^2.

I.1.4. Coordinate grid of remediated structures and land areas

Sketches of the facility were developed to document the locations of monitoring activities during the final remediation monitoring. The sketches, which include a reference coordinate grid, are provided in Figs 30–44.

I.2. REMEDIATION PLAN

The remediation plan identified the office as a non-impacted area; the shipping and receiving area and the machine shop as Class 3 areas; the change room, and packaging and inventory areas as Class 2 areas; and the laboratory as a Class 1 area. The area of the underground waste lines and tank were determined to be Class 1 areas (Tables 12 and 13).

I.2.1. Remediation activities

As low levels of contamination had been identified in the exhaust duct and stack, the filter bank and stack were removed and packaged as waste. The glovebox and fume hood were also removed and packaged as waste. The laboratory benches and tables were removed and surveyed for clearance. Floor tiles in the laboratory were removed and packaged as waste. The passbox from the laboratory to the packaging and inspection room was removed and surveyed for clearance.

The laboratory was further decontaminated and all surfaces pressure washed and dried prior to monitoring. The wash water was collected in a temporary storage tank. Samples of the wash water were collected for analysis to demonstrate that ^{63}Ni contamination was not being released in excess of release limits which the environmental control regulatory body established as 0.1 Bq/mL.

Text cont. on p. 131.

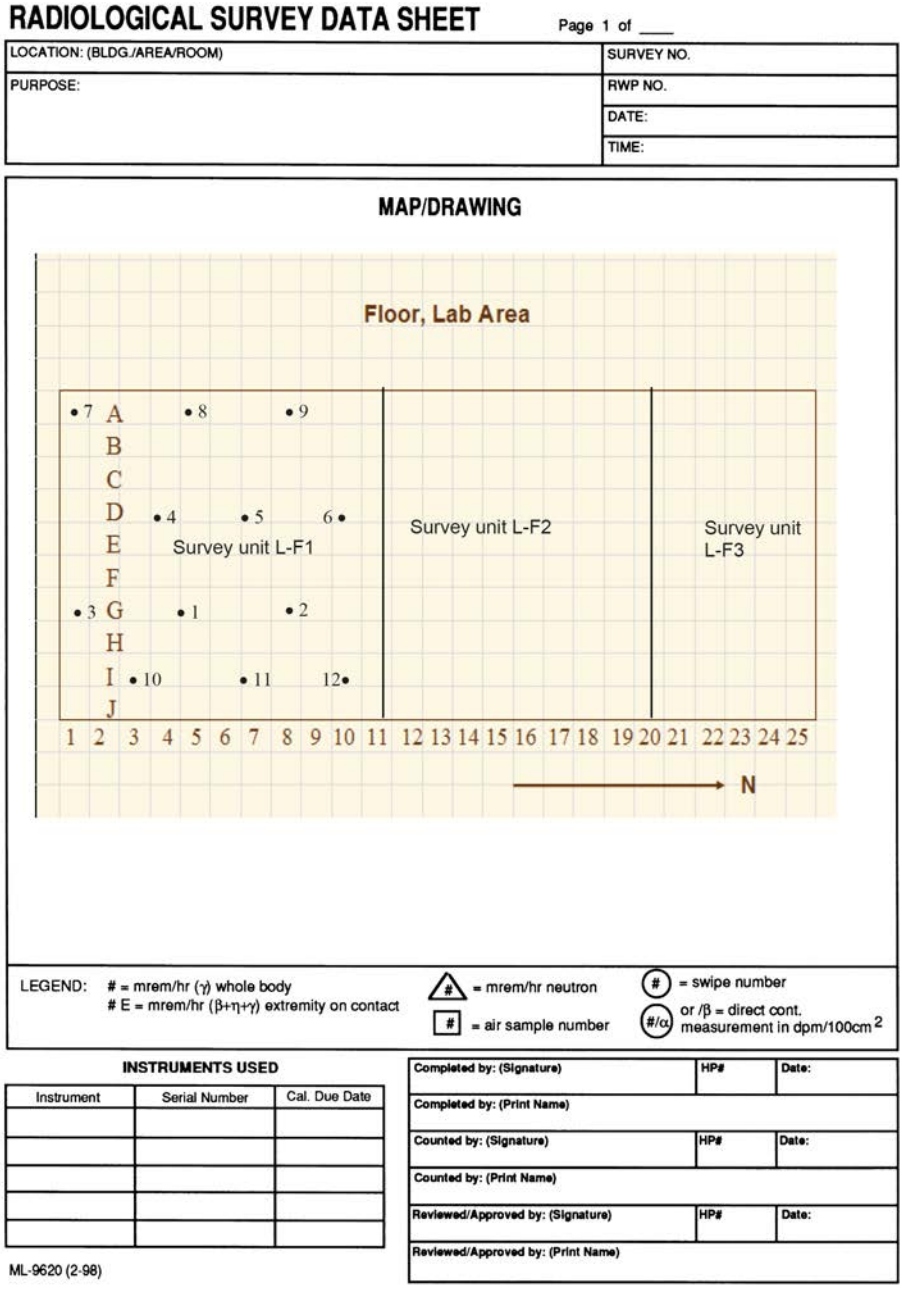

FIG. 30. Sketch of the laboratory area, floor.

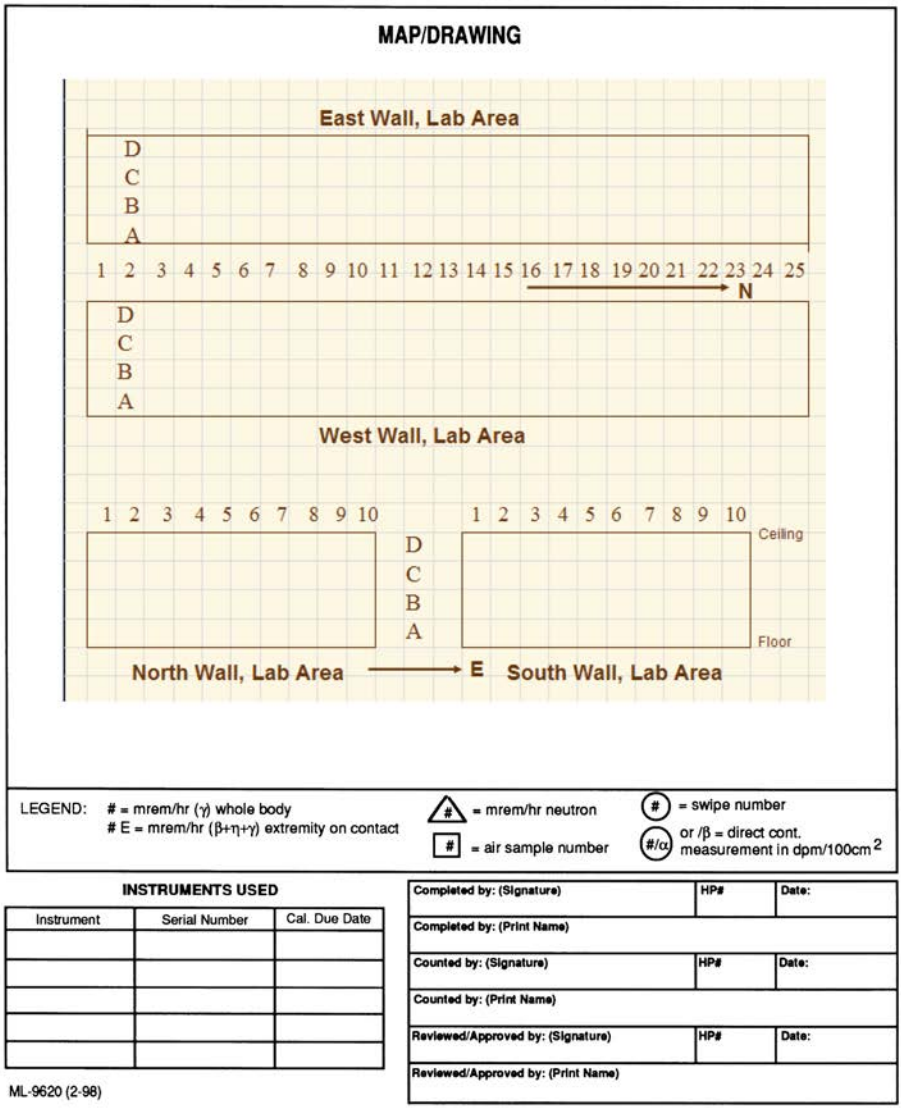

FIG. 31. Sketch of the laboratory area, walls.

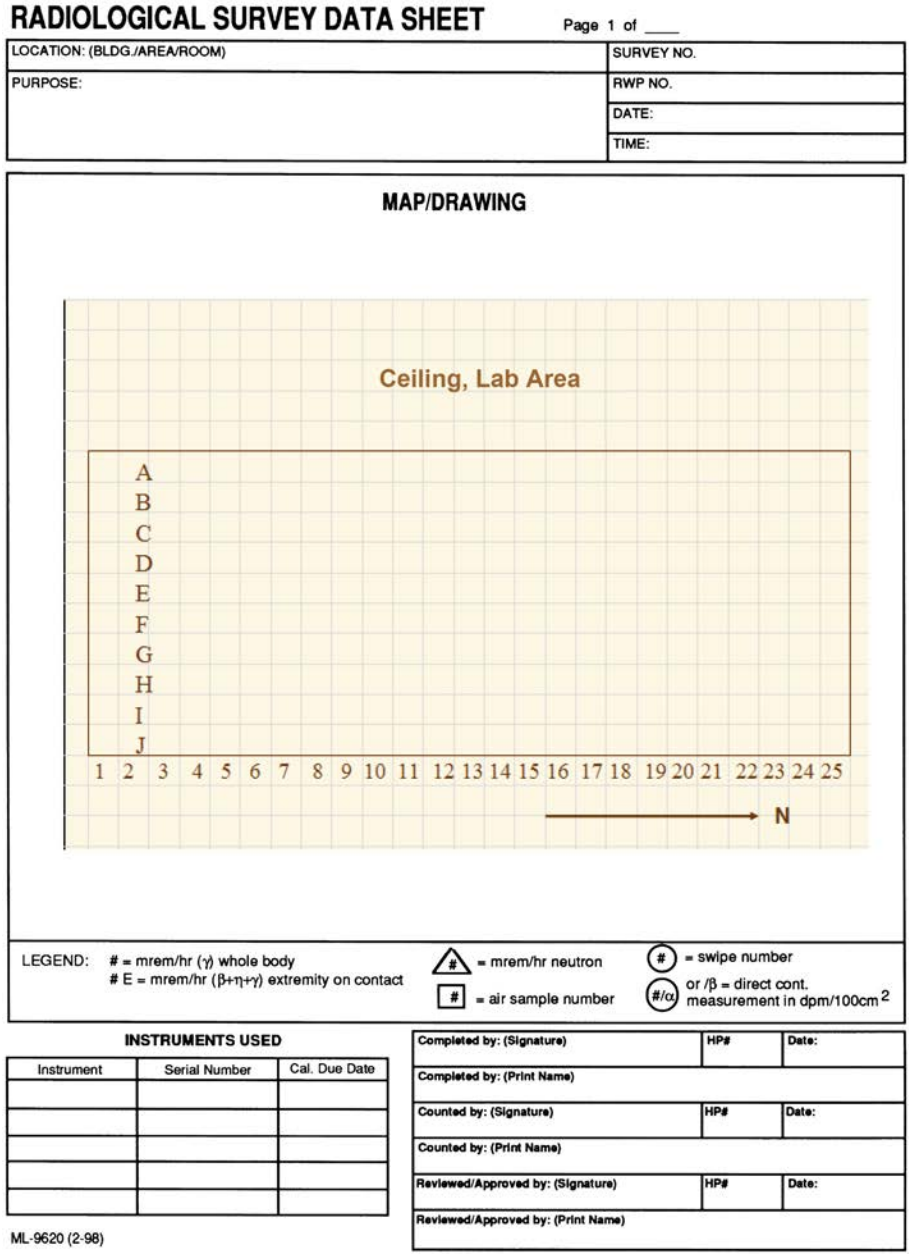

FIG. 32. Sketch of the laboratory area, ceiling.

FIG. 33. Sketch of the packaging and inventory area, floor and ceiling.

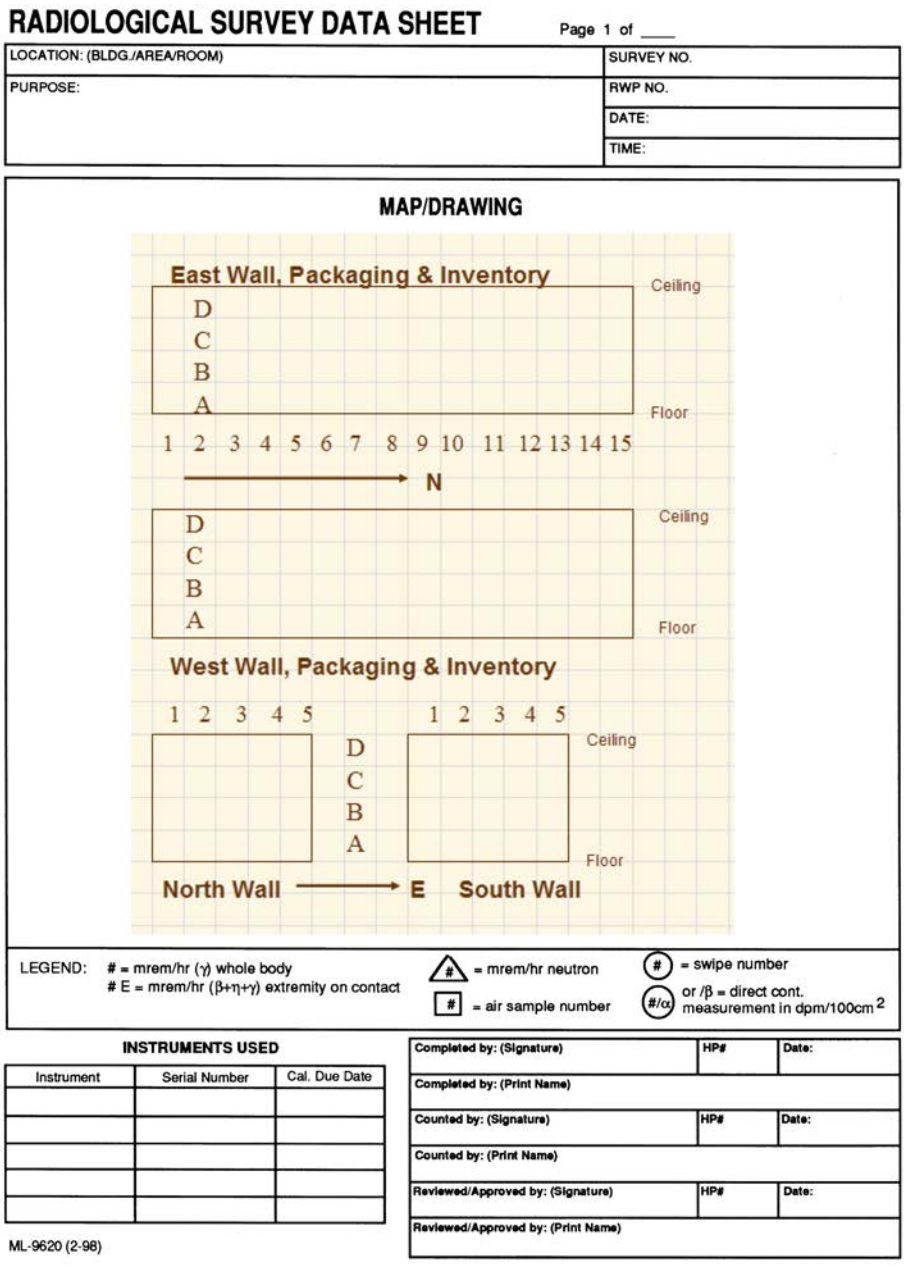

FIG. 34. Sketch of the packaging and inventory area, walls.

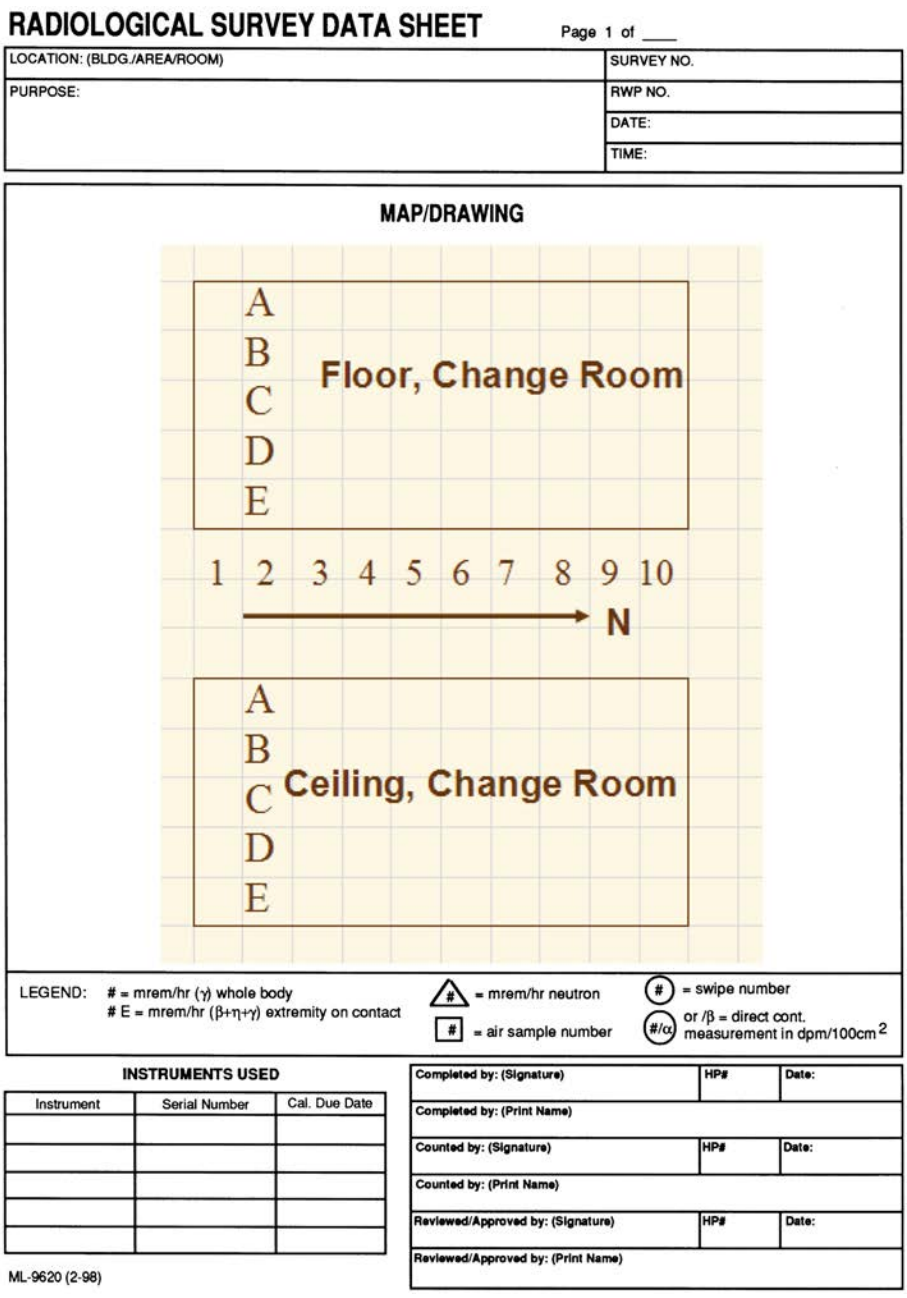

FIG. 35. Sketch of the change room, floor and ceiling.

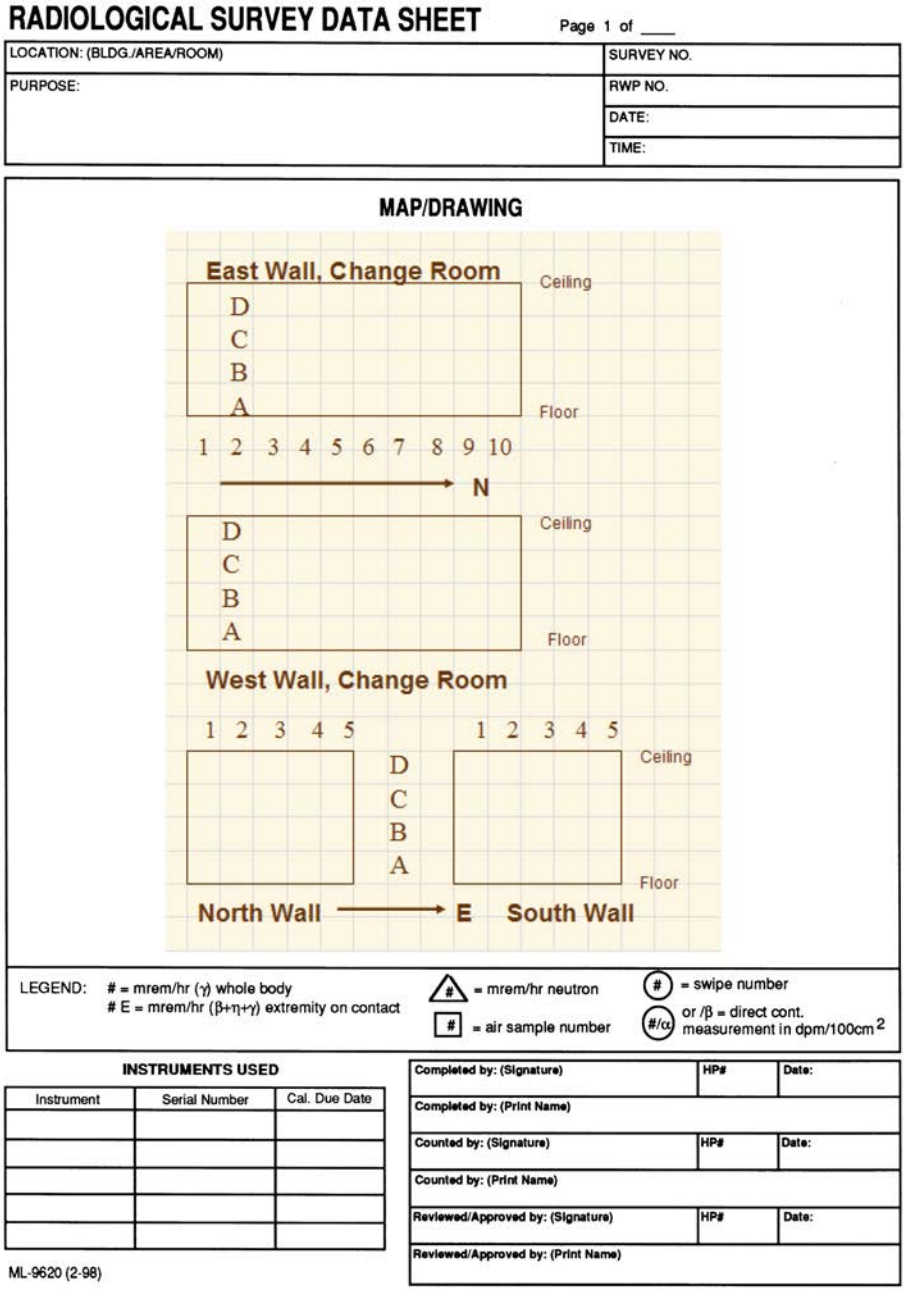

FIG. 36. Sketch of the change room, walls.

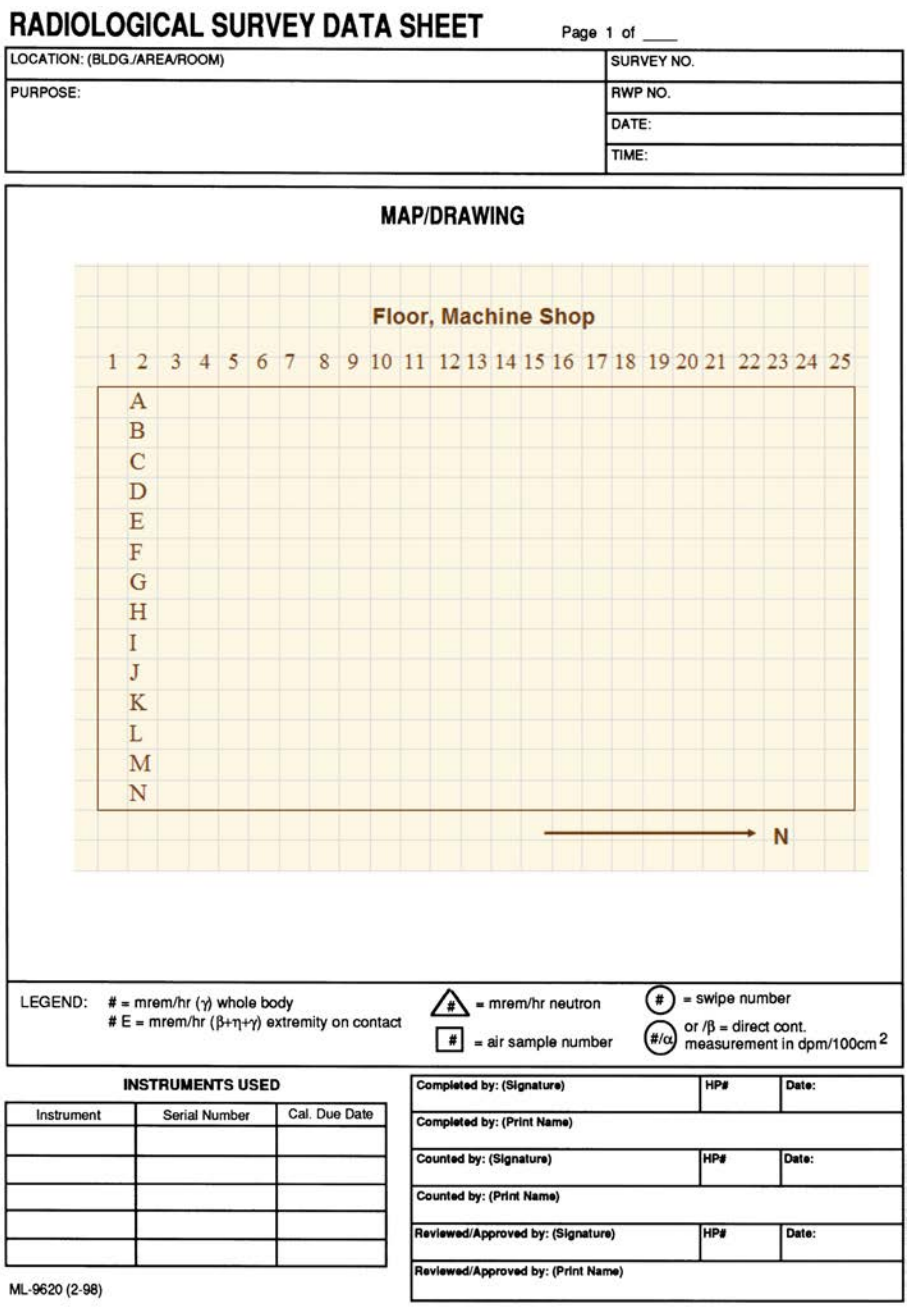

FIG. 37. Sketch of the machine shop, floor.

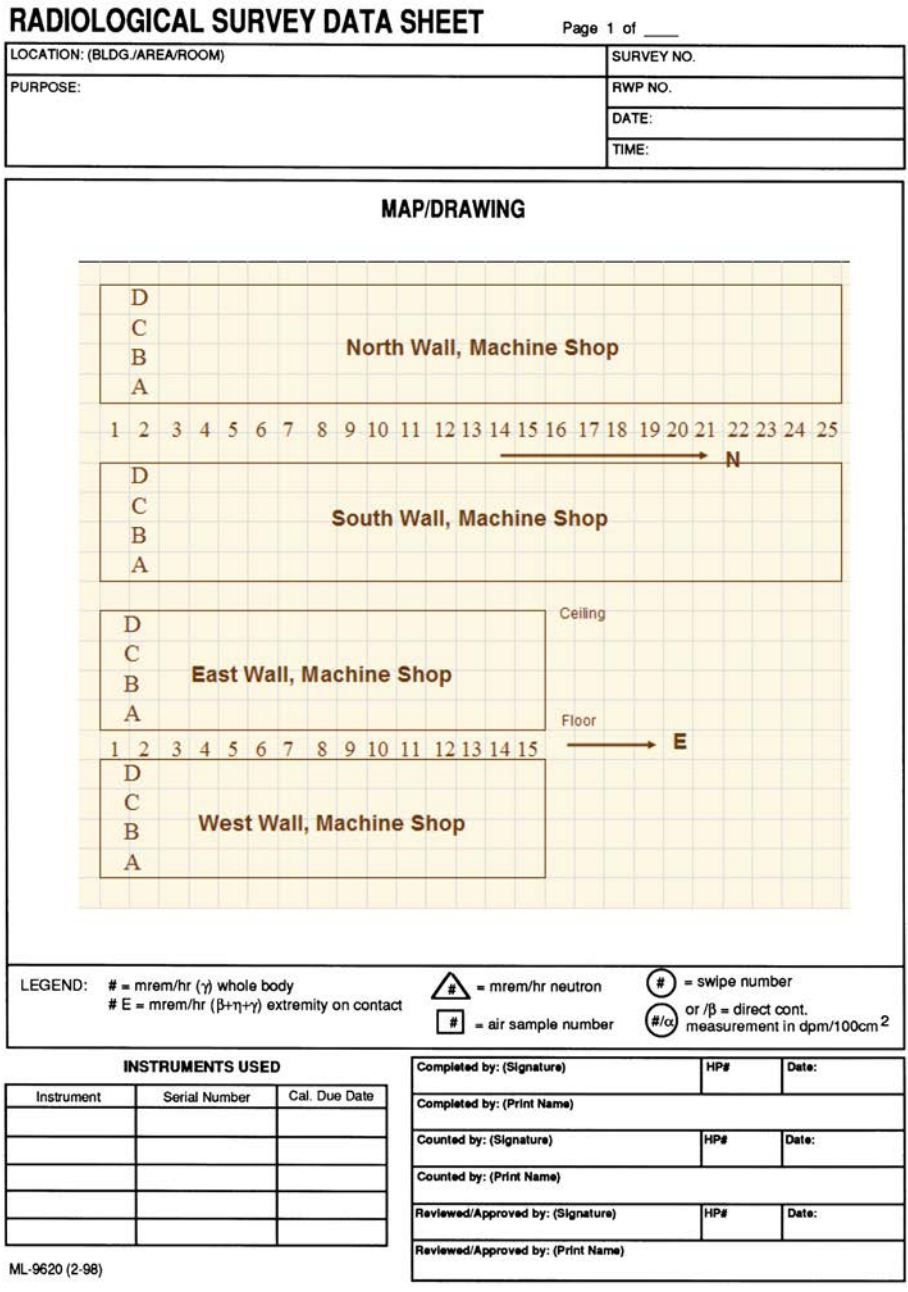

FIG. 38. Sketch of the machine shop, walls.

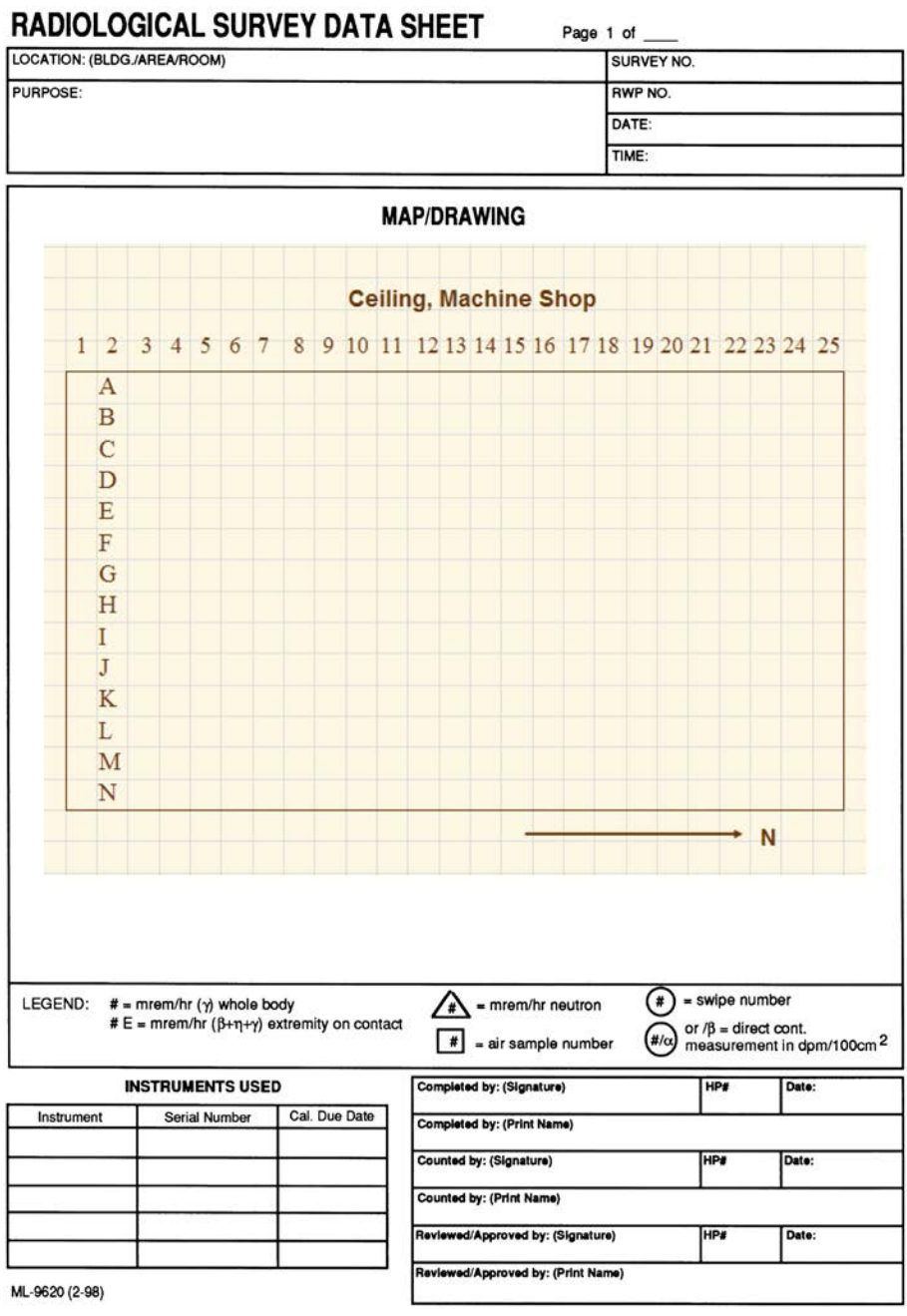

FIG. 39. Sketch of the machine shop, ceiling.

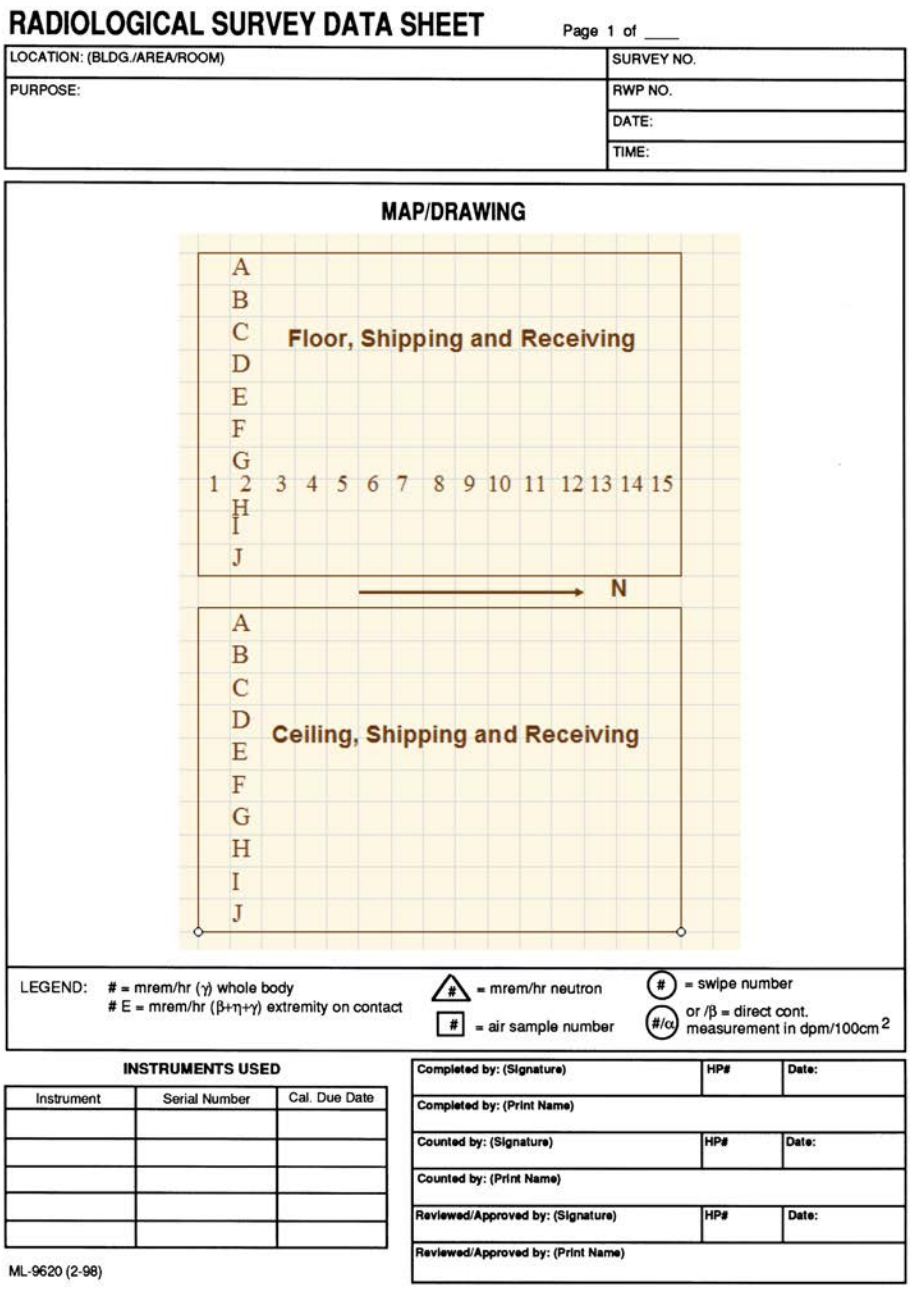

FIG. 40. Sketch of the shipping and receiving area, floor and ceiling.

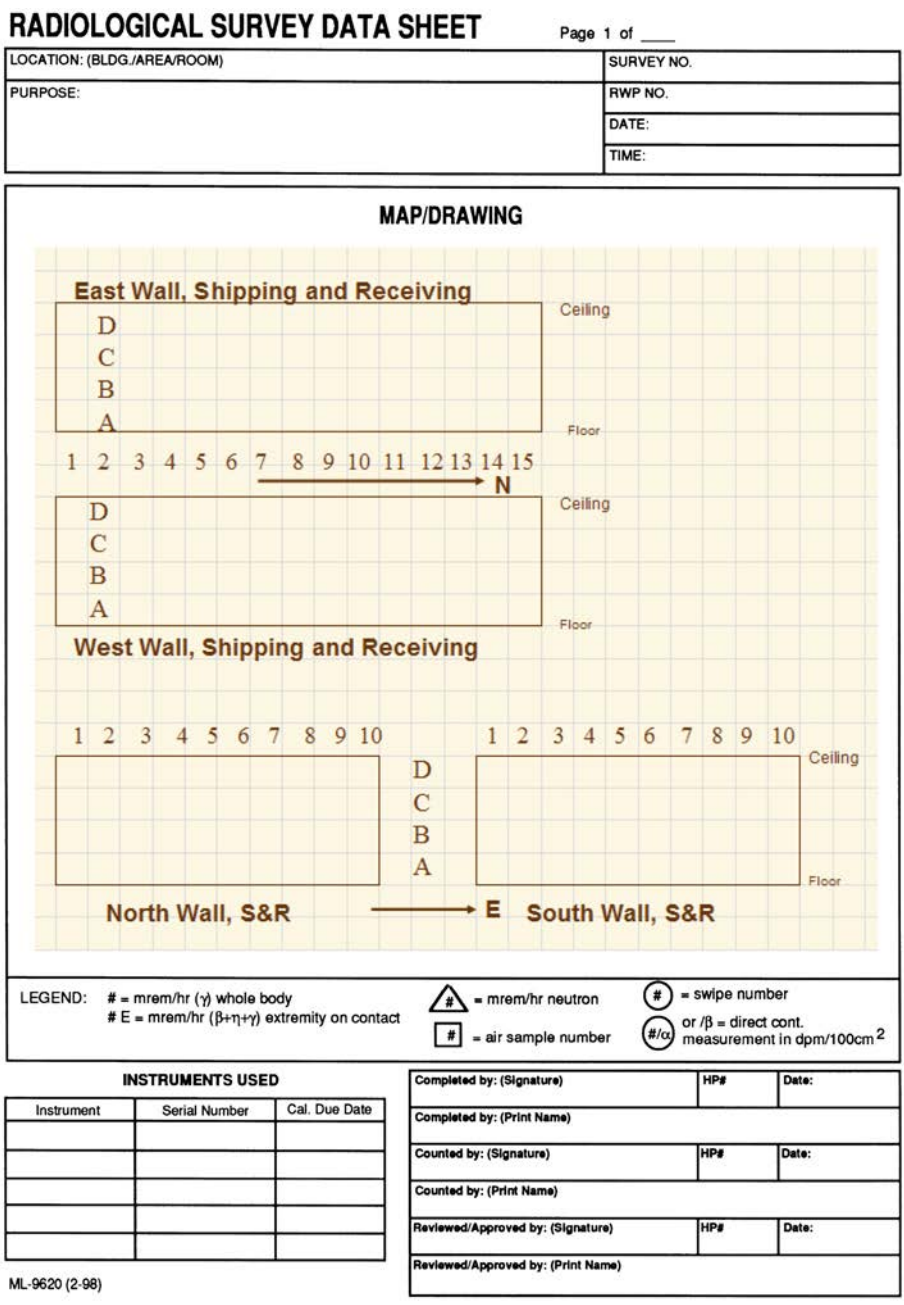

FIG. 41. Sketch of the shipping and receiving area, walls.

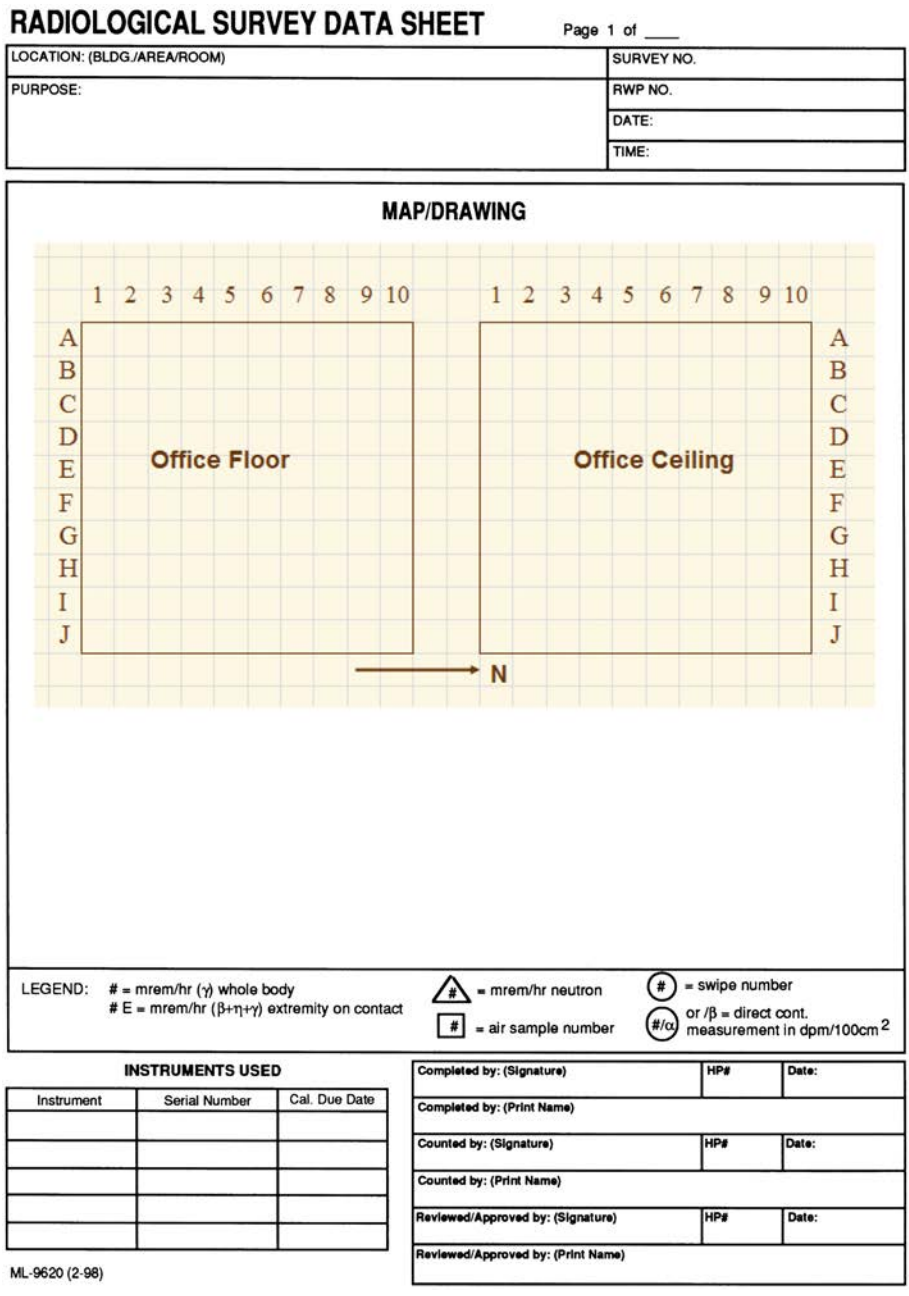

FIG. 42. Sketch of the office area, floor and ceiling.

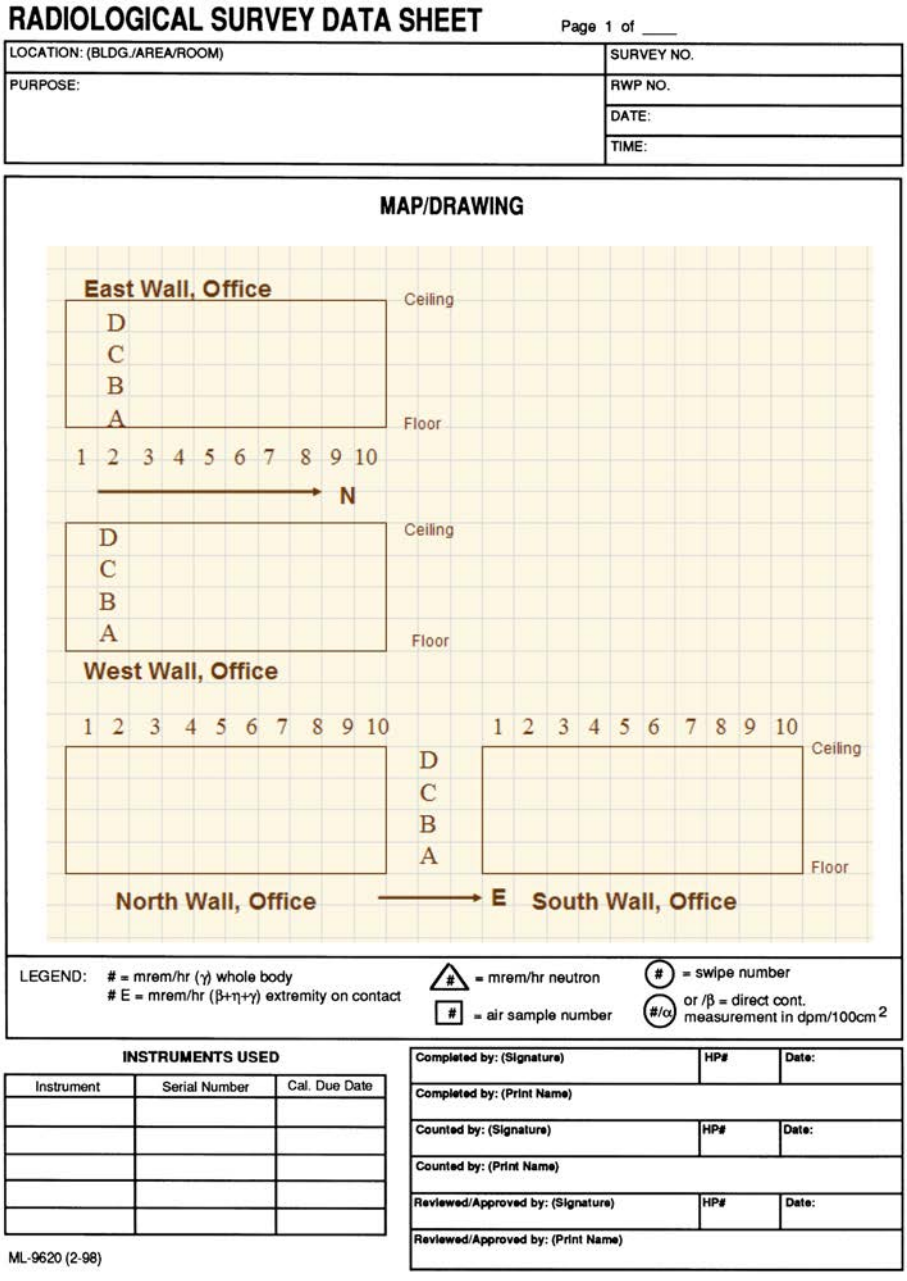

FIG. 43. Sketch of the office area, walls.

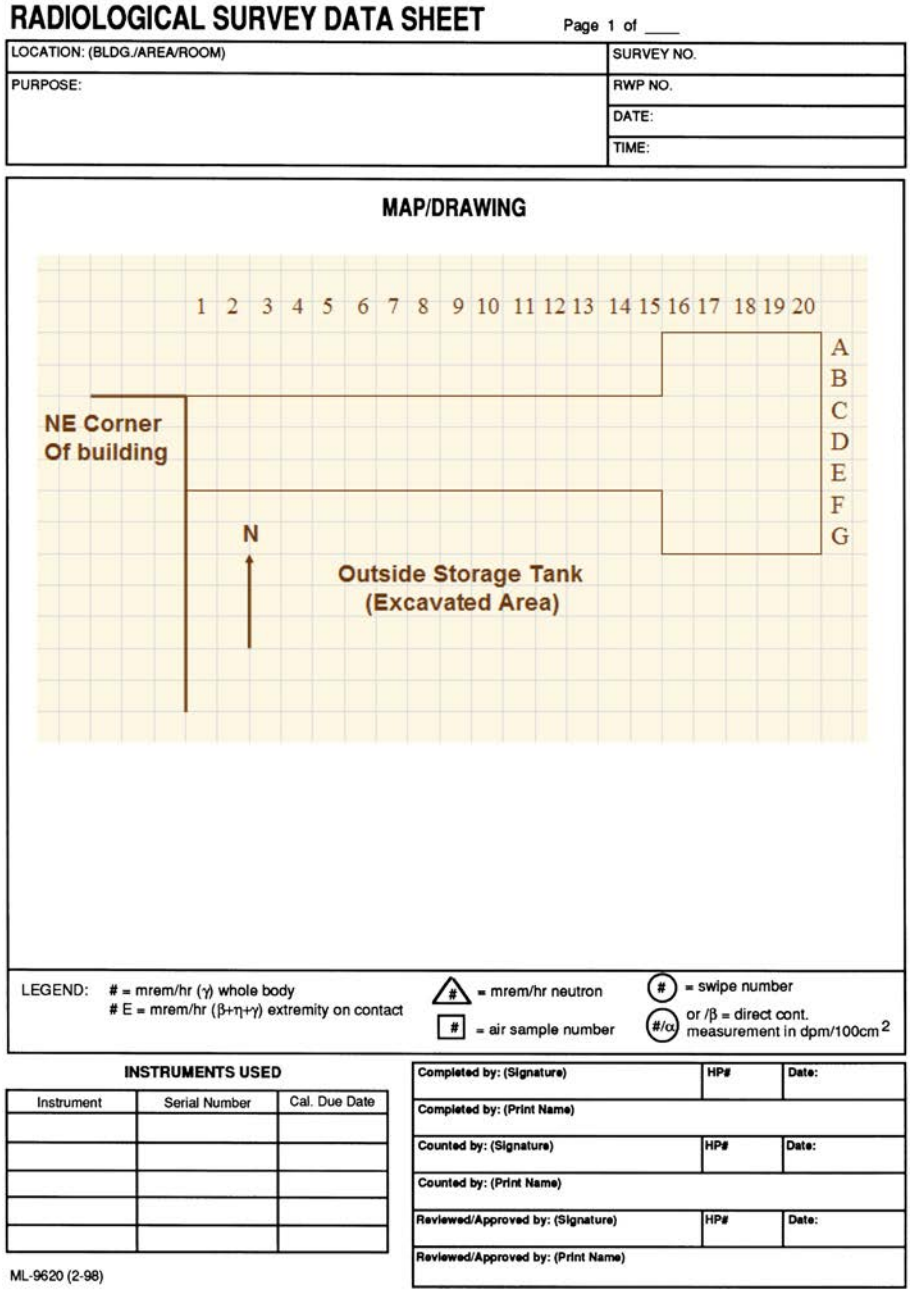

FIG. 44. Sketch of the excavated area.

TABLE 12. IDENTIFICATION OF SURVEY UNITS

Structure area	Classification	Designation	Description
Laboratory	Class 1	L-F1	The south part of the laboratory, floor only, 10 m by 10 m. Total area: 100 m^2. This area included laboratory benches (Fig. 30, Grids A.1–J.10).
		L-F2	The centre part of the laboratory, floor only, 10 m by 10 m. Total area: 100 m^2. This area included laboratory benches and a small area with the fume hood (Fig. 30, Grids A.11–J.20).
		L-F3	The north part of the laboratory, floor only, 10 m by 5 m. Total area: 50 m^2. This area included the glovebox, most of the fume hood, the filter bank and drain lines to the outside underground lines and storage tank (Fig. 30, Grids A.21–J.25).
	Class 2	L-W&C	This area includes the walls and ceiling. The wall area totals 320 m^2 and the ceiling includes an area of 250 m^2. This area is not expected to have any areas greater than the derived remediation criteria. 50% of the walls will be surveyed; 25% of the ceiling will be surveyed (Figs 31 and 32).
Change room, and packaging and inventory room	Class 2	CR-PI-F	Two rooms are combined for this survey unit. The floor area includes 75 m^2 from the packaging and inventory room and 50 m^2 from the change room. No contamination above the derived remediation criteria is expected in this survey unit. 50% of the floor area will be surveyed (Figs 33–36).

TABLE 12. IDENTIFICATION OF SURVEY UNITS (cont.)

Structure area	Classification	Designation	Description
	Class 3	CR-PI-W&C	The walls and ceiling of the change room, and packaging and inventory include: Change room Walls: 120 m^2 Ceiling: 50 m^2 Packaging and inventory Walls: 160 m^2 Ceiling: 75 m^2 The walls and ceiling in these two rooms are not expected to be contaminated. 10% of the area will be surveyed (Figs 33–36).
Machine shop, and shipping, receiving and storage areas	Class 3	MS-SR-3	The machine shop, and shipping, receiving and storage areas are not expected to be contaminated. The area includes: Machine shop Floor: 375 m^2 Walls: 320 m^2 Ceiling: 375 m^2 Shipping, receiving and storage Floor: 150 m^2 Walls: 60 m^2 Ceiling: 150 m^2 25% of the floors will be surveyed, 10% of the walls will be surveyed and 25 random measurements will be taken on the ceiling (Figs 37–41).

TABLE 12. IDENTIFICATION OF SURVEY UNITS (cont.)

Structure area	Classification	Designation	Description
Office area	Non-impacted	Not applicable	This area continues to be in use during the remediation of the facility and the performance of the final remediation monitoring (Figs 42 and 43).
Land area			
Underground lines and tank area	Class 1	LA-F&W-1	The survey unit includes the trench where the underground lines were removed and the area where the underground storage tank was removed. The trench from the underground lines excavation has a nominal depth of 2 m; the area where the tank was removed has a nominal depth of 3 m. The total area of the survey unit includes: Underground lines Floor: 30 m^2 Walls: 40 m^2 Tank Floor: 35 m^2 Walls: 63 m^2 The total area is 168 m^2 (Fig. 44). There are no survey instruments that can be used for practical monitoring of soil for Ni-63. Also, because the walls are included in the survey unit, 20% additional samples will be collected in addition to the recommended 20% additional samples for statistical considerations.

TABLE 13. FINAL STATUS SURVEY DESIGN BY CLASSIFICATION [46]

Class	Sampling	Scanning
1	Systematic	100% coverage
2	Systematic	10–100%
3	Random	Judgemental

The underground lines and tank were flushed, and the water sampled and released in accordance with the release criteria of 0.1 Bq/mL. Water that collected in the excavated areas during remediation was also sampled and released. The underground lines and tank were removed, along with the laboratory drains and packaged as waste. During the removal of the underground lines and tank, soil samples were collected and screened by the laboratory. The screening of soil samples took approximately 2 h, and had a detection limit of approximately 50 Bq/g. Once the samples were less than the detection limit, an additional 0.5 m of soil was removed and packaged as waste to provide assurance that the survey unit would be below the derived remediation criteria. The screening data from the final samples collected during remediation are provided later.

I.3. MONITORING DURING REMEDIATION

Remediation support surveys were conducted with a gas proportional probe connected to a ratemeter. This instrument is acceptable for performing surveys on clean, flat, smooth surfaces. Surfaces with detectable contamination were cleaned or removed. Once contamination was removed to below detectable activity, the area was secured (no entry or exit) until the scheduled final remediation monitoring was performed.

Other equipment in the facility was surveyed for clearance. Samples of electrical conduit were collected, cut lengthwise and flatted for direct measurement subsequent to clearance. Items to be cleared were surveyed for total contamination with a gas proportional detector connected to a ratemeter. If contamination levels on the item were below the clearance criteria, it was moved to a roped-off area with a tarp taped to the floor, and swipes were taken. If the swipes met the clearance criteria and the item was approved for clearance, the item was moved from the controlled area outside the building to await disposition.

I.4. PLANNING FOR FINAL REMEDIATION MONITORING

In consideration of NUREG-1507, Minimum Detectable Concentrations with Typical Radiation Survey Instruments for Various Contaminants and Field Conditions [19], the instrument of choice for scanning and static measurements for surface contamination is the gas proportional detector. An instrument with both scalar and ratemeter modes of operation was selected, with a 126 cm^2 probe, operated in the beta plus alpha mode.

I.4.1. Calculating instrument detection limits

The background count rate for this example has been determined to be 255 cpm based on 1 min count times and an instrument counting efficiency of 0.055 counts per disintegration.

The detection limits for the instrument in scanning mode are calculated as follows:

$$\mathrm{MDA}_{\mathrm{scan}} = \mathrm{MDCR}/[p^{1/2} \times \varepsilon_{\mathrm{i}} \times \varepsilon_{\mathrm{s}} \times (A/100) \times C] \quad (3)$$

where

MDCR is $s_i\,(60/i)$;

and s_i is the minimum detectable net source counts in the interval i which, in this example, assumes that the scanning will proceed at one probe width per second, and is determined from the specified performance level and square root of the background level.

$$s_i = d'(b_i^{1/2}) \quad (4)$$

where

d' is based on the permissible true positive and desired false positive proportions from Table 14.

In this example, the regulatory body has directed a true positive proportion of 0.95, and because the MDA is a small per cent of the derived remediation criteria, the operator chooses a value corresponding to a low probability of false positives, in this case, 0.10, so that d' is 2.92.

TABLE 14. TRUE AND FALSE POSITIVE PROPORTIONS

False positive proportion	True positive proportion							
	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95
0.05	1.90	2.02	2.16	2.32	2.48	2.68	2.92	3.28
0.10	1.54	1.66	1.80	1.96	2.12	2.32	2.56	2.92
0.15	1.30	1.42	1.56	1.72	1.88	2.08	2.32	2.68
0.20	1.10	1.22	1.36	1.52	1.68	1.88	2.12	2.48
0.25	0.93	1.06	1.20	1.35	1.52	1.72	1.96	2.32
0.30	0.78	0.91	1.05	1.20	1.36	1.56	1.80	2.16
0.35	0.64	0.77	0.91	1.06	1.22	1.42	1.66	2.02
0.40	0.51	0.64	0.78	0.93	1.10	1.30	1.54	1.90
0.45	0.38	0.52	0.66	0.80	0.97	1.17	1.41	1.77
0.50	0.26	0.38	0.52	0.68	0.84	1.04	1.28	1.64
0.55	0.12	0.26	0.40	0.54	0.71	0.91	1.15	1.51
0.60	0.00	0.13	0.27	0.42	0.58	0.82	1.02	1.38

In addition:

ε_i is the instrument efficiency as discussed in ISO-7503 [29] which, in this case, is 0.055 counts per disintegration;
ε_s is the source efficiency, which for ^{63}Ni is 0.25;
p is the performance of the surveyor to recognize when the instrument has detected the minimum number of counts above background to be called a 'hit' and, in absence of actual data, is estimated to be 0.5;
$A/100$ is the probe size divided by 100 so the units will be in dpm/100 cm^2;

and C corresponds to other factors that affect the performance of the measurement, including correction factors for standoff distance. In NUREG-1507 [19], a correction factor of 0.196 has been determined for a standoff distance of 1 cm which will be required by the procedure while the probe is scanning the surface.

So, in this case, the MDA_{scan} can be calculated as:

$$MDCR = d' \times b_i^{½} \times (60/i)$$

$$= 2.92(\sqrt{255 \times 1/60}) \times (60/1)\ (s) = 361\ (\text{net cpm})$$

$$MDA_{scan} = 361\ (\text{cpm})/\sqrt{0.5} \times 0.055\ (\text{counts per disintegration}) \times 0.25 \times 0.196 \times 1.26$$

$$MDA_{scan} = 150\ 346\ (\text{dpm})/100\ (\text{cm}^2) \text{ or } 25\ \text{Bq/cm}^2 \quad (5)$$

During the conduct of the survey, this instrument will be used to scan the area specified in the description in the table of survey units. If 50% coverage is required, then 50% of the 1 m^2 grids will be scanned with this instrument at a rate of one probe width per second. It should be noted that there is no guidance on how to determine which 50% of the surface is covered. Normally, it is randomly chosen to provide uniform coverage of the surface. During the scanning process, if the surveyor notices an increase in counts, he will perform a static measurement and record the value of the static measurement on the data sheet. The MDA_{static} is calculated in a somewhat different manner because of procedural factors; for example, the performance of the surveyor is not considered since a digital reading will be obtained at the conclusion of the measurement.

The MDA_{scan} is approximately 25% of the derived remediation criteria for structures. For a more thorough treatment of this calculation, see section 6.7.2 of

MARSSIM [9]. To determine the static MDA, the background was determined in 1 min intervals, but the sample is counted using the integration feature of the instrument for 0.1 min. Therefore, the more general form of the MDA calculation is used as follows:

$$MDA_{static} = \{3 + 3.29[(R_B \times T_{S+B})(1 + T_{S+B}/T_B)]^{½}\}/K \times T_{S+B} \quad (6)$$

where

R_B is the background count rate;
T_{S+B} is the count time of the sample plus background, or gross sample count rate;
T_B is the background count time;

and K is the conversion factor(s) to achieve appropriate units.

In this case, MDA_{static} is calculated as:

$$MDA_{static} = \{3 + 3.29[255 \times 0.1(1 + 0.1/1)]^{½}\}/0.055 \times 0.25 \times 1.26 \times 0.1 \text{ (min)}$$

$$MDA_{static} = 11\ 790 \text{ (dpm)}/100 \text{ (cm}^2\text{)} \text{ or } 2.0 \text{ Bq/cm}^2$$

As expected, MDA_{static} is less than MDA_{scan}.

I.4.2. Choosing the test

Before choosing the appropriate test to use for the analysis of the data, the hypotheses must be stated. In this case, because the contaminant of concern is not present in the background, the null hypothesis can be stated as:

H_0: The ^{63}Ni concentration in the survey unit exceeds the derived remediation criteria.

The alternative hypothesis is:

H_1: The ^{63}Ni concentration in the survey unit does not exceed the derived remediation criteria.

From the characterization survey, it was determined that no other radionuclides were present from these operations, and ^{63}Ni is not present in the background at a level of significance compared to the derived remediation criteria. Based on this information, it is appropriate to use the sign test.

I.4.3. Determining the number of measurements (samples)

To determine the number of samples for each survey unit, there must be an expectation of how much residual contamination is present. If it is expected that considerable residual contamination exists, it is necessary to perform further remediation. If the residual contamination is generally low but there are small areas of elevated activity, these have to be identified and cleaned. The number of samples required depends on the estimate of the median activity remaining following remediation, and the variability in the activity. It also depends on the degree of confidence the regulatory body expects from the test, and how willing the operator is to potentially fail to release a survey unit that actually passes, but because of the statistical process the null hypothesis is not rejected. The probability of this occurring decreases as more samples are taken, but then the cost of the survey increases as more samples are taken. Typically, the regulatory body requires a 0.95 assurance that the unit will not pass if indeed the concentration exceeds the derived remediation criteria. This corresponds to $\alpha = 0.05$. The operator chooses his risk based on schedule, cost and other factors. The operator often chooses a 0.90 probability that the survey unit will fail when, in fact, it actually passed. This corresponds to $\beta = 0.10$.

The median concentration and variability in concentration are usually estimated from either the characterization data for Class 2 or Class 3 survey units, or from the remediation support survey for Class 1 areas. Normally, only the last measurements from the remediation support survey are considered, since if a measurement exceeds the derived remediation criteria, additional remediation would be performed, and then a subsequent measurement would be taken to confirm that the remediation was successful. If it was, then further samples are not necessary.

In this example, only two of the survey units will be analysed; the south survey unit on the laboratory floor and the land area where the underground lines and tank were removed.

I.4.4. Estimating the relative shift

In this example, for survey unit L-F1, the number of samples required is calculated based on the assumption that there is little chance of contamination levels in excess of the derived remediation criteria following remediation.

The relative shift can be estimated by the following equation:

$$\Delta/\sigma_s = (\text{derived remediation criteria} - \text{median contamination concentration})/\sigma_s \quad (7)$$

where σ_s is the estimated standard error of the ^{63}Ni concentration.

In this case, the derived remediation concentration is 100 Bq/cm^2, the estimated median concentration 50 Bq/cm^2 and the estimated standard error 1 Bq/cm^2. Thus, the relative shift is calculated to be 2.0.

To estimate the number of samples required for a survey unit, the decision error levels in this example are $\alpha = 0.05$ and $\beta = 0.10$.

The number of sample points in survey unit L-F1 is calculated as follows:

$$N = 1.2(Z_{1-\alpha} + Z_{1-\beta})^2/4(\text{Sign p} - 0.5)^2 \quad (8)$$

where

1.2 is an arbitrary factor for increasing the sample size to account for sample losses, etc., and still meeting the statistical requirements of the test;

$Z_{1-\alpha}$ is the factor corresponding to decision error level α;

and $Z_{1-\beta}$ is the factor corresponding to decision error level β.

These factors are found in Table 15 (section 5 of MARSSIM [9]) and Sign p is determined from Table 16 (from section 5 of MARSSIM [9]):

$$N = 1.2(1.645 + 1.282)^2/4(0.977250 - 0.5)^2 \quad (9)$$

$N = 11.3$ (~12 samples)

Thus, twelve measurements (samples) will be taken in survey unit L-F1.

TABLE 15. PERCENTILES REPRESENTED BY SELECTED VALUES OF α AND β [9]

α (or β)	$Z_{1-\alpha}$ (or $Z_{1-\beta}$)	α (or β)	$Z_{1-\alpha}$ (or $Z_{1-\beta}$)
0.005	2.576	0.100	1.282
0.010	2.326	0.150	1.036
0.015	2.241	0.200	0.842
0.020	1.960	0.250	0.674
0.025	1.645	0.300	0.524

TABLE 16. VALUES OF SIGN p FOR GIVEN VALUES OF THE RELATIVE SHIFT, Δ/σ WHEN THE CONTAMINANT IS NOT PRESENT IN BACKGROUND [9]

Δ/σ	Sign p	Δ/σ	Sign p
0.1	0.539828	1.2	0.884930
0.2	0.579260	1.3	0.903199
0.3	0.617911	1.4	0.919243
0.4	0.655422	1.5	0.933193
0.5	0.691462	1.6	0.945201
0.6	0.725747	1.7	0.955435
0.7	0.758036	1.8	0.964070
0.8	0.788145	1.9	0.971284
0.9	0.815940	2.0	0.977250
1.0	0.841345	2.1	0.993790
1.1	0.864334	2.2	0.998650

I.4.5. Choosing the locations of the measurements (samples)

The measurement locations are determined by using a stratified random pattern. In this case, the initial location is determined by application of a random generator. An example process is found in Table 17 (from MARSSIM [9]). Other locations are identified by calculation in a regular pattern. In this case, a triangular pattern will be used. To determine the distance between measurement (sample) locations:

$$L = \text{sqrt}[A/(0.866 \times N)] \quad (10)$$

where

A is the area of the survey unit;

and N is the number of sample locations.

In the case of survey unit LF-1, the sample grid is established from:

L = sqrt[100 (m^2)/(0.866 ×12)] = 3.1 m

The first location is picked at random. The second location is 3.1 m away, the third another 3.1 m away. At the edge of the survey unit, a second row of sample points is established 3.1 m away from the first row, and Sample 4 is located between Samples 1 and 2. The pattern continues as shown in Fig. 30. The results of the measurements are recorded on the radiological survey data sheet (RSDS) data page in Fig. 45.

I.5 PERFORMANCE OF FINAL REMEDIATION MONITORING

During the final remediation survey, scans are performed over given areas. In Class 1 areas, this is typically 100%. In Class 2 or 3 areas, a portion of the areas is scanned. This scanning is conducted independently of the statistical measurements. The percentage of areas surveyed depends on factors including potential, professional judgement, and perhaps input from other interested parties. Normally, 25–75% is appropriate.

In the laboratory, a Class 1 area, each 1 m^2 of floor was scanned. Of wall surfaces, 50% of the 1 m^2 areas were scanned, and 25% of the 1 m^2 areas of the ceiling were scanned. In any scanning measurement, if the scan MDA is exceeded, a static measurement is taken and recorded on the RSDS continuation page. In addition, the specified number of measurements is determined in the final remediation monitoring plan for each class area. Each of these measurements is also recorded on the data page. During the planning process with the other interested parties, it was decided that measurements that were obtained from static measurements would be included with the specified measurements.

Each survey unit would have an RSDS sheet. More than one survey unit might be captured on a sketch but each survey unit has its own distinct identification.

The sample locations for the land area are determined in the same manner, except that because instrumentation is not available to scan the area, the analytical results of the samples will provide the basis for release. To determine the relative shift, samples collected during the remediation phase may be used to determine the expected concentration and standard deviation. In this case, it is prudent to take a few additional samples to provide more power for the statistical tests.

RADIOLOGICAL SURVEY DATA SHEET									
Survey No. _____								Page ____ of ____	
Sample	Direct dpm/100 cm^2	Swipes (dpm/100 cm^2) α	Swipes (dpm/100 cm^2) β–	Comments	Sample	Direct dpm/100 cm^2	Swipes (dpm/100 cm^2) α	Swipes (dpm/100 cm^2) β–	Comments
1	42 355			G4					
2	21 615			G8					
3	31 775			G1					
4	28 220			D3					
5	37 590			D7					
6	19 115			D10					
7	24 160			A1					
8	37 460			A4					
9	41 785			A8					
10	33 355			J3					
11	27 820			J7					
12	34 170			J10					
B4	51 505			$>MDA_{scan}$					
H10	39 360			$>MDA_{scan}$					
I2	41 450			$>MDA_{scan}$					
Completed by: _____					Reviewed by: _____				
Date: _____					Date: _____				

FIG. 45. Measurement results from the laboratory floor, survey unit 1.

I.6. ANALYSIS OF FINAL REMEDIATION MONITORING RESULTS

I.6.1. Preliminary data evaluation

The locations of samples that were collected in survey unit LF-1 are documented in Fig. 30. The results of the measurements are recorded on the

RSDS data page in Fig. 45. The following quantities are determined from the data presented in Table 17.

I.6.2. Frequency plot

A frequency plot (Fig. 46) has been developed based on the data from Fig. 45. The frequency plot verifies that there are no distribution inconsistencies that might prompt the evaluator to review methods and instrumentation, or to collect additional data. A bimodal distribution might be a cause for further investigation. However, based on the small number of samples, this frequency plot is not definitive.

TABLE 17. PRELIMINARY DATA

Quantity	Value	Application
Range	19 115–51 505 dpm 3.19–8.58 Bq/cm^2	The range is 5.39 Bq/cm^2 which is 3.7 standard deviations. This ratio does not indicate that the data are widely distributed. A wide distribution would indicate a need for a frequency plot or posting plot as a means to further evaluate the data.
Mean	34 116 dpm 5.69 Bq/cm^2	The mean is a small per cent of the derived remediation criteria. The initial determination is that the evaluation should continue. If the mean exceeded the derived remediation criteria or was close, more remediation would be indicated.
Median	34 170 dpm 5.69 Bq/cm^2	The difference between the mean and median is a small percentage of the standard deviation; this indicates that the data are generally normal, although the small number of samples may not support this assumption.
Standard deviation	8842 dpm 1.47 Bq/cm^2	From this value, the relative shift can be recalculated. The initial estimate was 2.0. The actual relative shift based on these data is 64, a very high number that exceeds the original estimate and confirms that the number of samples was adequate.

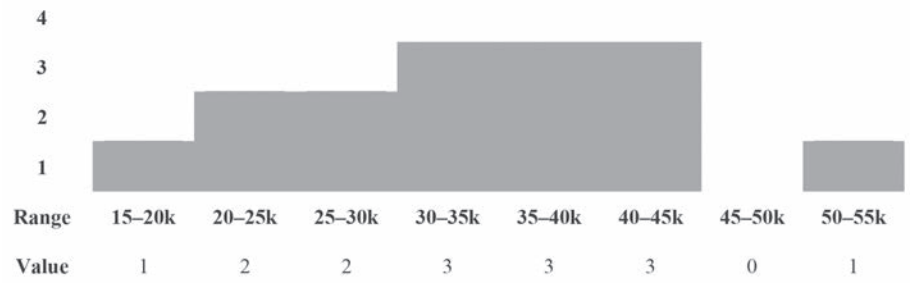

FIG. 46. Frequency plot.

	1	2	3	4	5	6	7	8	9	10
A	24				37			42		
B				**51**						
C										
D			28				38			19
E										
F										
G	32			42				22		
H										**39**
I		**41**								
J			33				28			34

FIG. 47. Posting plot.

I.6.3. Posting plot

A posting plot (Fig. 47) confirms that the contamination is evenly distributed, and does not indicate that any area needs to be investigated further.

I.6.4. Test selection

I.6.4.1. Structure

As the contaminant is not in background, and the derived remediation criteria are much greater than background, an appropriate test to use is the sign test. To use this test, the tasks described below are performed.

Null hypothesis: The median concentration of ^{63}Ni in the survey unit is greater than the derived remediation criteria of 100 Bq/cm^2. This will be true unless the test indicates that it needs to be rejected in favour of the alternative, which does not empirically state that the alternative is true but that the alternative is preferable.

Alternative hypothesis: The median concentration of ^{63}Ni in the survey unit is less than 100 Bq/cm^2.

Each measurement is listed in the order collected and subtracted from the derived remediation criteria, maintaining the sign (+ or –). Every attempt is made not to have a measurement exactly equal to the derived remediation criteria because if the difference is zero, the measurement is discarded and the measurement dropped from the total number of measurements.

The number of positive values is counted (Table 18). The value is compared to Table 19 (from MARSSIM [9] and NUREG-1505 [46]). If the total number of positive values exceeds the critical value listed in the table, the null hypothesis is rejected.

TABLE 18. RESULTS OF MEASUREMENTS

Measurement	Value (Bq/cm^2)	Difference
1	7.06	+92.94
2	3.60	+96.40
3	5.30	+94.70
4	4.70	+95.30
5	6.27	+93.74
6	3.19	+96.81
7	4.03	+95.97
8	6.24	+93.76
9	6.96	+93.04
10	5.56	+94.44
11	4.64	+95.36
12	5.70	+94.31
13	8.58	+91.42
14	6.56	+93.44
15	6.91	+93.09
N = 15		S+ = 15

TABLE 19. CRITICAL VALUES FOR THE SIGN TEST STATISTIC *S*+ [46]

	Alpha								
N	**0.005**	**0.01**	**0.015**	**0.02**	**0.025**	**0.03**	**0.035**	**0.04**	**0.045**
4	4	4	4	4	3	3	3	2	2
5	5	5	5	4	4	3	3	3	2
6	6	6	5	5	5	4	4	3	3
7	7	6	6	6	5	5	4	4	3
8	7	7	7	6	6	5	5	4	4
9	8	8	7	7	6	6	5	5	4
10	9	9	8	8	7	6	6	5	5
11	10	9	9	8	8	7	6	6	5
12	10	10	9	9	8	7	7	6	6
13	11	11	10	9	9	8	7	7	6
14	12	11	11	10	9	9	8	7	7
15	12	12	11	11	10	9	9	8	7
16	13	13	12	11	11	10	9	9	8
17	14	13	12	12	11	10	10	9	8
18	14	14	13	12	12	11	10	10	9
19	15	14	14	13	12	11	11	10	9
20	16	15	14	14	13	12	11	11	10

In Table 19, the entry argument of $\alpha = 0.05$ and $N = 15$, the critical value k is 11. Since $S+$ is 15 (all values less than the derived remediation criteria), the null hypothesis is rejected in favour of the alternative. For more table values, see appendix I of MARSSIM [9].

I.6.4.2. Land area

As there is no field instrument that can detect ^{63}Ni in soil, a scan survey cannot be performed. Following removal of the underground lines and tank, samples were taken and screened by the laboratory. Once the samples were less than 50 Bq/g, an additional 0.5 m of soil was removed to ensure that the contamination had been removed to a practical level. The final remediation survey was then conducted.

The remediation support survey soil samples before the last 0.5 m of soil was removed were as presented in Table 20.

From these data, the following were calculated: mean = 26.85, median = 24.5, standard deviation = 14.8 and relative shift = 5.1.

As the relative shift is >3, the median does not have to be so low, and the lower boundary of the grey region, approximated by the median, can be raised to a higher level, in this case to 55.6. This allows the average reading for the sign test to be increased, resulting in a greater probability that the survey unit will pass. Again, using $\alpha = 0.05$ and $\beta = 0.10$ as arguments from the table, the number

TABLE 20. RESULTS FROM THE SOIL SAMPLES

Land area, following removal but prior to final remediation monitoring	
Location (see RSDS)	Concentration (Bq/g)
B2	38
C7	20
E12	49
D14	8.2
A16	27
C19	41
E18	22
G17	9.6

of samples corresponding to a relative shift of 3.0 is 11. The additional 20% of samples increases this calculated value to 14, since the number of samples required is not rounded but rather always expressed up to the next highest integer.

The sample locations are chosen in the same manner as described before, with the first sample location chosen at random. The distance between sample points is 2.9 m.

$$L = \text{sqrt}[168\ (\text{m}^2)/(0.866 \times 14)] = 3.72\ (\text{m}) \quad (11)$$

The sample locations are shown in Fig. 48. It should be noted that although the sample grid was based on 14 samples, because 15 samples actually fit on the sketch, that many samples are collected. From the off-site laboratory analytical values recorded on the RSDS data page (Fig. 49), none of the samples exceeds the derived remediation criteria. As none of the samples exceeded the derived remediation criteria, the unit passes or, more correctly stated, the null hypothesis is rejected.

I.7. OPERATOR'S DECISION ON COMPLIANCE AND SPECIFICATION OF FOLLOW-UP ACTIONS

As both the structures and land areas were confirmed to meet the derived remediation criteria, as agreed with other interested parties during the planning stages of the project, the site can be released in accordance with the specifications described in the planning documents. No further remediation is required, no additional calculations or interpretations need to be made and no additional restrictions are warranted on the basis of this final remediation survey.

A checklist of tasks was used to perform final remediation monitoring and more specifically:

— The area to be remediated, the expectations of the remediation effort and the methods to evaluate whether the remediation has been successful (the DQOs process or similar technique) are identified.
— Derived remediation criteria are identified.
— A common grid is established and a coordinate system generated for areas to be included in the final remediation monitoring. Drawings (sketches) are made, and the coordinate system on the actual area identified.
— Decision errors from the regulatory body are specified.
— It is determined whether the contaminant of concern is present in background.

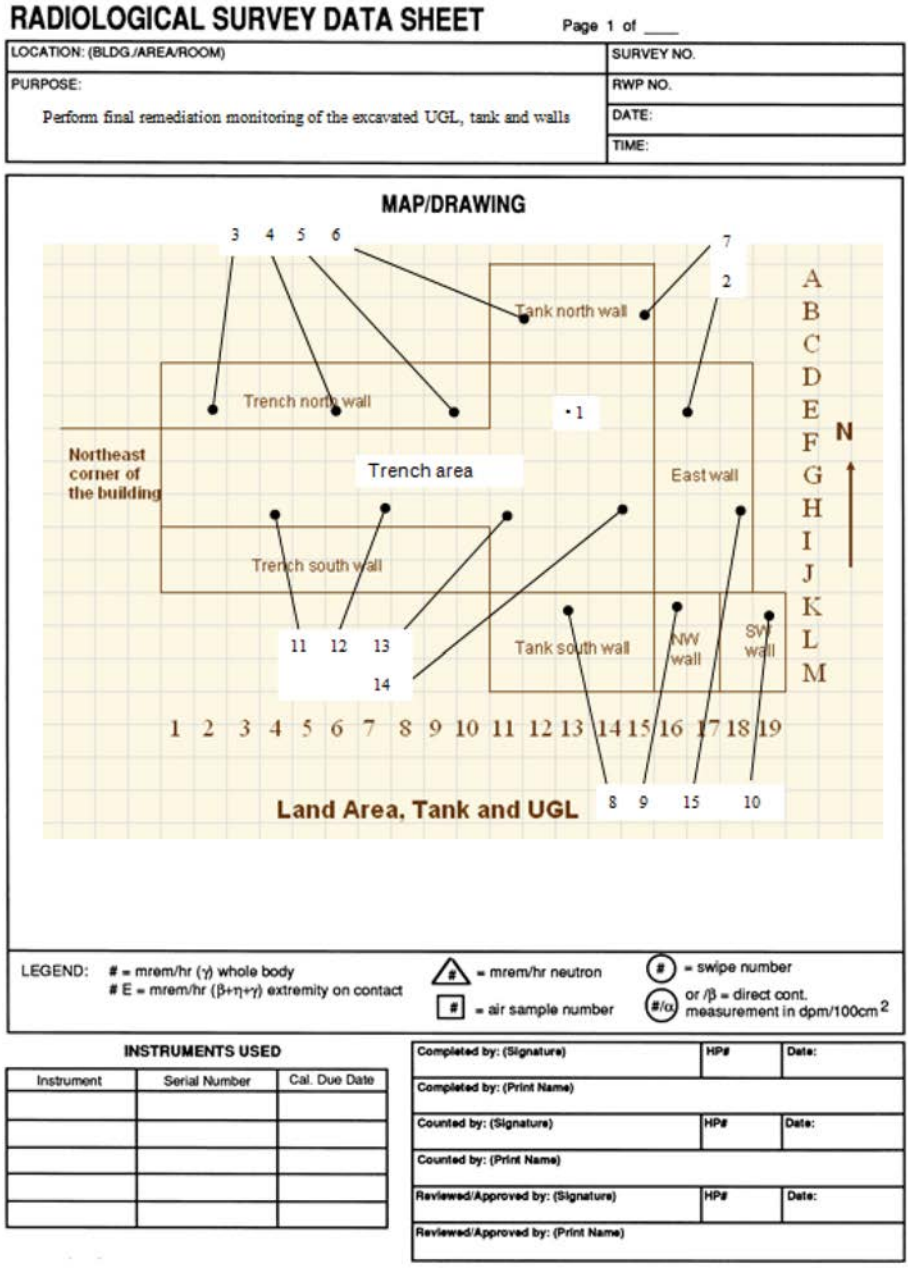

FIG. 48. Sample locations, land area.

RADIOLOGICAL SURVEY DATA SHEET

Survey No. _____ Page ____ of ____

Sample No.	Direct (pCi/g)	Swipes (dpm/100 cm²) α	Swipes (dpm/100 cm²) β–	Comments	Sample No.	Direct _____	Swipes (dpm/100 cm²) α	Swipes (dpm/100 cm²) β–	Comments
1	29			E13					
2	18			E16					
3	9.1			E2					
4	22			E6					
5	38			E9					
6	5.5			B12					
7	27			B15					
8	36			K13					
9	51			K16					
10	29			K19					
11	8.8			H4					
12	53			H7					
13	33			H11					
14	14			H15					
15	29			H18					

Completed by: _____ Reviewed by: _____

Date: _____ Date: _____

FIG. 49. Measurement results, land area.

— Reference areas are identified if necessary.
— The types of measurements that will be sufficient to demonstrate that the area meets the remediation criteria are determined.
— The test to be performed on the data are identified.
— The classification of areas is determined.
— Survey units are identified.
— Remediation is performed.
— The variability in the level of the contaminant(s) of concern is estimated.

— The relative shift for each survey unit is estimated.
— The number of measurements (samples) needed to support the statistical test for each survey unit is determined.
— The acceptable upper limits of contamination for smaller areas within a survey unit are determined.
— The spacing between measurement locations is determined.
— An initial starting point for the first measurement is identified.
— Each measurement (sample) location is identified.
— The scan MDA and static MDA required are determined.
— The instruments of choice are identified.
— Analytical laboratories that can analyse the different sample types at the required sensitivity in a timely manner are identified.
— Survey procedures for use of instruments to meet MDA requirements are generated.
— QA procedures for these programmes and others, as necessary, are developed:
  • Instrument performance (calibration, functional checks, MDA calculations, etc.);
  • Surveillance of monitoring activities;
  • Audit of laboratory practices;
  • Data interpretation;
  • Data management.
— The following programmes and others, as necessary, and accompanying procedures are developed:
  • Data review;
  • Record keeping;
  • Training.
— Monitoring (measurements and samples) of remediated areas and reference areas (if necessary) is performed.
— Data analysis is performed.
— Statistical test assumptions are verified before applying the test to each survey unit.
— Statistical tests, as agreed during the planning stage, are conducted.
— Test results are compared to derived remediation criteria.
— A report that includes the results for each survey unit is generated.

Appendix II

APPROACH FOR DEVELOPMENT OF RELEASE CRITERIA FOR MULTIPLE CONTAMINANTS

II.1. INTRODUCTION

Application of dose based release criteria for situations where multiple radionuclide contaminants are present requires consideration of the contribution of each radionuclide relative to its specific authorized criterion (release concentration) value. The particular radionuclides present, the nature of the contamination (i.e. surface activity or volumetric), and the methods used to evaluate the radiological conditions (e.g. direct measurements of gross activity, radionuclide specific analyses or use of surrogate measurements on soil samples) necessitate different approaches for developing appropriate criteria for implementing monitoring for radionuclide mixtures. This Safety Report describes the methods for determining release criteria if multiple contaminants are present.

II.2. DETERMINING THE MIX OF RADIONUCLIDE CONTAMINANTS

(1) The sample results (activity or concentration) for each of the analyses from radionuclide specific analyses are tabulated. Non-detects (MDAs or MDCs) are considered as actual levels. Samples with low activity levels may result in MDA or MDC values which are a significant fraction of the total activity and will incorrectly overestimate the contributions from non-detectable radionuclides in the total contaminant mix. Therefore, samples containing higher levels of the representative radionuclide mix of interest have to be selected for this determination.
(2) These results are adjusted by eliminating radionuclides not associated with the licensed operation and by subtracting average natural background levels.
(3) The total activity or concentration of adjusted levels in the sample and the individual fractional contribution of each radionuclide of interest is calculated.
(4) Steps 1–3 are repeated for all of the samples from the area of interest.
(5) The average and standard deviation of the fractional contribution of each radionuclide of concern are calculated.

(6) The 95% upper confidence level (UCL) fractional contribution of each radionuclide of concern that is potentially present is calculated. The method described in section 8.5.5 of Ref. [44] is one approach for determining UCL.

(7) The total of the radionuclide UCL fractions is calculated and the individual UCL values normalized, based on a total of one (i.e. unity). The resulting values represent the fractional activity contributions (f_1 through f_n) for radionuclides 1 to n through the monitored area of interest.

Some areas being evaluated for release may have few, if any, locations with activities of hard to detect radionuclides above analytical detection levels. Therefore, there may be limited data available for determining the average and variability of relative radionuclide ratios. In such situations, radionuclide mixes for other areas for monitoring with the potential for similar contamination need to be used, if available. If multiple data sets are not available, a suggested approach is to base the mixture determinations on data that are available and to use analyses of release samples to confirm (or modify) the radionuclide mix used for planning and design.

II.3. ESTABLISHING CRITERIA FOR A MIXTURE

For multiple contaminants, the unity rule is applicable. This means that the sum of the ratios of concentrations present to their respective release criteria for each radionuclide present must be ≤1.

$$\frac{C_1}{RC_1} + \frac{C_2}{RC_2} + \ldots + \frac{C_n}{RC_n} \leq 1 \tag{12}$$

where

C_n is the concentration of each individual radionuclide (1, 2, … n);

and RC_n is the guideline value for each individual radionuclide (1, 2, … n).

In other words, there is not a single guideline for the radionuclide mix, but rather a group of guidelines applicable to each radionuclide and a unity rule applicable to the sum of the ratios.

Using the fractional activity contributions of radionuclide in a mixture, determined from Appendix I, levels of certain contaminants (e.g. hard to detect

radionuclides) can be inferred, based on analyses of contaminants that are easier to measure. The measured radionuclide is referred to as the surrogate. The *RC* for the surrogate radionuclide is adjusted for the contributions of inferred contaminants. If C_1, …, C_n are the concentrations of radionuclides 1 to n, RC_1, …, RC_n are the release criterion values for radionuclides 1 to n, and R_2 to R_n are fractional contributions (C_2/C_1, …, C_n/C_1) of radionuclides 2 to n, then adjusted *RC* for the surrogate radionuclide is calculated by:

$$RC_{\text{surrogate}} = 1/[1/RC_1 + R_2/RC_2 + \ldots R_n/RC_n] \quad (13)$$

The ratio of the concentration of the surrogate radionuclide to its $RC_{\text{surrogate}}$, thus, accounts for all radionuclides for which contributions are inferred by the surrogate measurement.

II.4. ESTABLISHING THE GROSS SURFACE ACTIVITY CRITERIA OF A MIXTURE

Using the fractional activity contributions of radionuclides, determined from Appendix I, the gross surface activity release criterion value (SAC_{gross}) are calculated by:

$$SAC_{\text{gross}} = \frac{F}{\frac{f_1}{RC_1} + \frac{f_2}{RC_2} + \ldots + \frac{f_n}{RC_n}} \quad (14)$$

where

f_1 through f_n are the activity fractions of radionuclides 1 through n, with radionuclide specific surface activity criteria RC_1 through RC_n, respectively;

and *F* represents the total fraction of detectable radionuclides in the mixture.

An alternative to deriving SAC_{gross} based on the fractional activity contributions is to identify the most conservative release criteria for the identified radionuclides present and use the release criterion value for that radionuclide in the above calculation.

If one or more of the radionuclides present is not detected by the gross measurement, the gross measurement may serve as a surrogate for the undetected

radionuclides by adjusting the SAC_{gross} to account for the activity fractions of the undetected radionuclides by:

$$SAC_{adjgross} = \frac{1}{\frac{1}{SAC_{gross}} + \frac{R_2}{RC_2} + ... + \frac{R_n}{RC_n}} \quad (15)$$

where R_2 through R_n represent the ratio of the activity fractions f_2, of the non-detectable radionuclides, 2 through n, respectively, to the total fraction of detectable radionuclides in the mixture, i.e. f_n/F.

Appendix III

UTILIZATION OF AVAILABLE INFORMATION FOR THE SITE

Identification and evaluation of the available site specific historical data (e.g. historical records, knowledge of the types of processes that caused contamination, experience gained elsewhere, public or individual memory) and characterization data prior to and during the remediation is essential for defining the strategy for monitoring for compliance with release criteria. As far as possible, the information needs to include the nature of contamination, quantities (e.g. size, volume, mass, length), physical and chemical properties (e.g. soil), geology, hydrology, demographics, flora, fauna, etc.

The needed information may include process or activities knowledge to determine contamination conditions, whether some material may have been activated by neutrons; and whether the site may have been contaminated as a consequence of an accident (the radionuclide vector may then be somewhat different from the radionuclide vector due to normal operations).

An important source of information is individual memory. In addition to the available documentation, it is necessary to interview people who worked on the site (these people are often retired at the time of the interview) in order to compile information which has not been recorded, but which is important for a better knowledge of the radiological situation of the site. The type of information that can be obtained concerns:

— Any incident that occurred on the site but is not mentioned in the documentation;
— Past activities which could induce contamination of the soil.

Historical information provides insight regarding the past activities, incidents or accidents that were originally responsible for contamination of the site. This assists the licensee (or authorized organization) in identifying potential contaminants, their levels and distribution on the site. A general picture of the initial conditions can then be formulated. Site history may also include a description of prior controlling or remedial activities and information about site uses in the period between the contaminating event and the present. Possible changes in contaminant distributions, radionuclide levels and potential migration to adjacent sites, and the presence of subsurface contamination of equipment, structures and wastes may be inferred from such information.

Monitoring data obtained during the characterization and from monitoring during the remedial action can provide useful information that confirms the types

of contaminants, levels and distribution. Such information provides confidence and assurance regarding the level of site knowledge and whether additional data and information are needed. The recent monitoring results and information also provide important planning details, such as current and potential future site uses, media which may be potential exposure and migration pathways, and accessibility of the site for monitoring purposes. It is important to note, in this regard, that data from monitoring during other investigation and remediation phases may be used for demonstrating compliance with criteria, provided that the data are of sufficient quantity and reassured quality, and that conditions have not changed since those data were developed.

Appendix IV

COMMON MONITORING INSTRUMENTS

TABLE 21. SUMMARY OF RADIATION DETECTORS WITH APPLICATIONS TO ALPHA MONITORING [9]

Detector type	Detector description	Application	Remarks
Gas proportional	<1 mg/cm^2 window; probe area: 50–1000 cm^2	Surface scanning; surface contamination measurement	Requires a supply of appropriate fill gas
	<0.1 mg/cm^2 window; probe area: 10–20 cm^2	Laboratory measurement of water, air and smear samples	
	No window (internal proportional)	Laboratory measurement of water, air and smear samples	
Air proportional	<1 mg/cm^2 window; probe area: ~50 cm^2	Useful in low humidity conditions	
Scintillation	ZnS(Ag) scintillator; probe area: 50–100 cm^2	Surface contamination measurements, smears	
	ZnS(Ag) scintillator; probe area: 10–20 cm^2	Laboratory measurement of water, air and smear samples	
	Liquid scintillation cocktail containing sample	Laboratory analysis, spectrometry capabilities	
Solid state	Silicon surface barrier detector	Laboratory analysis by alpha spectrometry	
Passive, integrating electret ion chamber	<0.8 mg/cm^2 window, also windowless; window area: 50–180 cm^2; chamber volume: 50–1000 mL	Contamination on surfaces, in pipes and in soils	Usable in high humidity and temperature

TABLE 22. SUMMARY OF RADIATION DETECTORS WITH APPLICATIONS TO BETA MONITORING [9]

Detector type	Detector description	Application	Remarks
Gas proportional	<1 mg/cm^2 window; probe area: 50–1000 cm^2	Surface scanning: surface contamination measurement	Requires a supply of appropriate fill gas
	<0.1 mg/cm^2 window; probe area: 10–20 cm^2	Laboratory measurement of water, air, smear and other samples	
	No window (internal proportional)	Laboratory measurement of water, air, smear and other samples	Can be used for measuring very low energy betas
Ionization (non-pressurized)	1–7 mg/cm^2 window	Contamination measurements; skin dose rate estimates	
Geiger–Mueller	<1 mg/cm^2 window; probe area: 10–100 cm^2	Surface scanning; contamination measurements; laboratory analyses	
	Various window thicknesses; probe face: a few square centimetres	Special scanning applications	
Scintillation	Liquid scintillation cocktail containing sample	Laboratory analysis; spectrometry capabilities	
	Plastic scintillator	Containing measurement	
Passive, integrating electret ion chamber	7 mg/cm^2 window, also windowless; window area: 50–180 cm^2; chamber volume: 50–1000 mL	Low energy beta including H-3 contamination on surfaces and in pipes	Usable in high humidity and temperature

TABLE 23. SUMMARY OF RADIATION DETECTORS WITH APPLICATIONS TO GAMMA MONITORING [9]

Detector type	Detector description	Application	Remarks
Gas ionization	Pressurized ionization chamber; non-pressurized ionization chamber	Exposure rate measurement	
Geiger–Mueller	Pancake (<2 mg/cm^2 window); or side window (~30 mg/cm^2)	Surface scanning; exposure rate correlation (side window in closed position)	Low relative sensitivity to gamma radiation
Scintillation	NaI(Tl) scintillator, up to 5 cm by 5 cm	Surface scanning; exposure rate correlation	High sensitivity; cross calibrate with pressurized ionization chamber (or equivalent) or for specific site gamma energy mixture for exposure rate measurements
	NaI(Tl) scintillator; large volume and 'well' configurations	Laboratory gamma spectrometry	
	CsI or NaI(Tl) scintillator; thin crystal	Scanning; low energy gamma and X rays	Detection of low energy radiation
	Organic tissue equivalent (plastics)	Dose equivalent rate measurements	
Solid state	Germanium semiconductor	Laboratory and field gamma spectrometry and spectroscopy	
Passive, integrating electret ion chamber	7 mg/cm^2 window, also windowless; window area: 50–180 cm^2; chamber volume: 50–1000 mL		Usable in high humidity and temperature

Appendix V

EXAMPLE OF A QUALITY MANAGEMENT PROGRAMME DESIGN

The quality management programme needs to be designed primarily to ensure that:

- Relevant requirements and criteria relating to monitoring are clearly defined and met.
- Management arrangements (organization, roles and responsibilities of managers, other staff members; competency, detailed instructions and procedures) are in place and have been applied. For large projects, a person trained in the field of quality management needs to be appointed, to be responsible for the development and implementation of the quality management programme.
- An adequate monitoring strategy is selected, reviewed, approved and implemented, and if necessary modified, and arguments properly documented.
- Selection, calibration, maintenance and testing are carried out for all equipment involved in the monitoring.
- Suitable monitoring, sampling and measuring instrumentations have been selected, reviewed, approved, implemented and their use confirmed.
- Procurement control, including subcontractors, services, is adequately planned and implemented, with a particular focus on laboratory measurements, and on maintenance and calibration of equipment.
- Verification of results has been undertaken. Inter-laboratory comparisons with split samples are a useful check. Occasional repeat in situ measurements by supervisory staff are recommended. These need to be at unpredictable intervals. Many sites will have legitimate areas of higher gamma activity, for example, caused by the use of building materials with higher than normal natural levels. If these have been successfully identified during a gamma survey, this adds confidence that any other area with similar levels needed to be found. On sites without these, it is perfectly permissible to bury, temporarily, materials such as bricks, granite blocks or fertilizer in bags which have a suitable gamma activity. An action plan for cases of non-compliance is established.
- Recording and reporting is in place. This includes the safe keeping of appropriate key records (i.e. monitoring strategy, plan, procedures and results) relevant to the preparation and implementation of the monitoring after remediation. The quality management programme needs to put emphasis on documentation of the calibration, checking and testing

procedures, sample management and the proper reporting of results. Records of training, including the results of the demonstrated qualification, need to be maintained. The achievement of milestones, any significant equipment or instrument malfunctions, or discovery of unexpected materials characteristics (e.g. higher levels of contamination or significantly larger volumes than expected) need to be reported quickly following the approved route.

— The process of evaluating survey results is performed in accordance with documented procedures.
— Staff members are appropriately qualified, experienced and trained.
— Adequate auditing of the sampling and analysis process is planned and undertaken. This is to check that results are assigned to the proper sample, material and location; such a procedure needs to include inspection of completeness and representativeness of samples; chain of custody; labelling of samples, field book notations, step by step recording and sample tracking.
— In case of non-compliance, proposed actions for adequate corrective actions are in place.
— Decision making and development of future actions is based on clear criteria and scope, objectives and boundaries of monitoring; identification of the inputs necessary for the decision making process; decision rule; and limits on decision errors.

It is important to note that the organization commissioning the review process will be expected to audit it.

V.1. CHECKS ON QUALITY DURING THE REMEDIATION PROCESS

Regular checks on quality need to be built in from the planning stage to the completion of the task. Once the monitoring programme has been set-up, the basic activity is checking that the measurements have been performed correctly, i.e. the people involved are following the method correctly and the equipment is working well enough.

It is essential that the measurement has actually been made. Automatic GPS based processes provide direct confirmation that the measurement has been performed at a particular time and place. Manual measurements are more difficult to monitor. It is essential to be aware that many of the measurements in this process can be demanding and also produce numbers at or close to background. This is particularly true where the remediation has been done conservatively or where large areas of the site have never been contaminated. This is a boring task

and there is a considerable temptation to make-up the results rather than make the measurement. Good supervision will keep this in check as will asking the people involved to record the actual indication, rather than 'background'. Using a scaler measurement rather than a ratemeter also helps, as it is possible to make a simple histogram of the readings and confirm that there are no unusually popular numbers. It is also easy to calculate the mean and standard deviation for an area where levels are expected to be reasonably constant. This will typically be shaped quite close to a normal distribution but with a slight tail towards the high end. Deviation from this shape needs to be looked into to confirm that the results agree with reality. Another approach is to leave something for people to find. For gross gamma measurements of a large area, there is often a gentle gradient in local dose rate across the site, as the geology and water content changes. Roads and footpaths often show up, either as more or less active than the surrounding soil. Building foundations are often clear, even when buried. In the absence of such features, bricks, granite blocks and bags of high potassium fertilizer can be temporarily buried to give confidence that the measurement has been performed and the local enhancement recorded.

In circumstances where there are no natural variations to be noted and no easy way of safely and temporarily enhancing local levels, QC is more difficult. Supervision and repeat readings are the only practical means.

Checking on the quality of the actual measurement is in many ways easier. For manual measurements, repeating a series of measurements will allow comparison of the two sets of results. The decision to be made is whether any significant difference is caused by the measurement not being performed in the first place or whether it is being caused by problems with the measurement itself. This could include equipment variations, staff skill and attention, or a failure to interpret the measurement correctly. The latter can be minimized by removing the need for manual calculation and interpretation by using a spreadsheet based interpretation method. Where significant differences are found, the cause has to be identified and a solution put in place. Sometimes, this will require work to be repeated. Each check needs to be recorded in the project log, together with any corrective action taken. This will make it clear to anyone auditing the work that a level of checking has been imposed throughout the project and that any weaknesses have been addressed.

For radiochemical laboratories particularly, use can be made of any accreditations to a nationally based inspection body. These will usually cover the methods employed and the quality checks to be made. Successful inspection records will give confidence that the laboratory is consistently producing results where the uncertainty does not exceed the declared value and that their management systems are in good order. In addition, it is completely permissible to send the laboratory samples which differ in some predictable way from the

majority delivered for analysis. For example, in an area where the level of contamination is generally measurable, while still acceptable, sending a geologically similar but essentially clean sample will make a useful check. The opposite is also useful — a high sample mixed in with a set of background samples. Mixing a sample carefully, splitting it and then sending in the samples out of order is useful.

V.1.1. Monitoring instrumentation qualification

The operator needs to establish an instrument qualification programme based on the use of the data that is obtained from the measurements. Since virtually all of the data will be used to compare readings to regulatory requirements, the data are required to be of the highest quality. In accordance with the quality management programme, instruments are calibrated in accordance with approved procedures at specified intervals following formal protocols. If the instruments will be stored at a remote location from the calibration facility, the instruments normally receive a receipt inspection when they arrive at the field storage location to ensure that they were not damaged during transit. The receipt inspection is performed in accordance with approved procedures. Control charts are developed for each instrument based on background readings and qualified sources. The sources used in the development of control charts do not necessarily have to be traceable to a national standard, but are controlled so that the radiation emission rate and quality will not change in an unpredictable manner over the time the source will be used. Each day the instrument is used, in accordance with approved procedures, the instrument is source checked with the qualified source, the results posted on the control charts, and the results evaluated to ensure that the instrument is operating properly.

It may be necessary for additional checks to be performed and documented on the control charts at the end of the day or more often. The decision regarding how often to perform source checks and to document them on the control charts is a function of a cost–benefit analysis. If the subsequent source check fails the control chart test, then all of the data collected since the last successful source check are suspect, and may need to be discarded (not actually ‘thrown out’ but rather not used in the final evaluation). The data are retained and qualified as unusable with the reason documented in the data package or log book.

V.1.2. Monitoring equipment test and calibration reports

Instrument calibration is the act of exposing an instrument in a radiation field of known intensity, then adjusting the controls on the instrument to match the intensity. The radiation characteristics of the source need to be traceable to an

official standards laboratory, such as the National Institute of Standards and Technology.

There are two aspects to calibration. One is a periodic test which is designed to demonstrate that any instrument is typical of type; this needs to be performed at least annually. This means that the instrument is responding in a way which agrees, within a reasonable margin, with the expectation derived from a type test. The type test is a collection of real measurements designed to produce information on an instrument's radiological, electrical and environmental characteristics. The type test can be performed by the manufacturer or by another body and is, generally, based on the relevant International Electrotechnical Commission standard. Once an instrument is proven to be typical of type, then other good quality information available on the instrument and its use can be used in the practical application. For example, a manufacturer or user may have worked out a gamma monitoring instrument's response in terms of counts per second per becquerel per gram for a particular set of sample volumes, matrices and radionuclides. This can prove very useful in the remediation process.

At a minimum, instrument calibration is usually required annually or more frequently if recommended by the manufacturer's specifications. A technical basis is required for any instrument whose calibration is scheduled at a frequency greater than annually. In addition, calibration may be necessary following maintenance or adjustment of parameters that affect an instrument's operations. More frequent instrument calibration may be required when the instrument is used under harsh field conditions.

When equipment is damaged and repaired, documentation is developed that, at a minimum, explains what occurred and what retesting is required. For a major repair, calibration of the instrument and associated probes are required.

Calibration is normally performed on a radiological instrument at two points on each scale. If a scalar instrument is not calibrated on each scale, a special use tag needs to be placed on the instrument indicating the scales that are not calibrated. However, if the instrument does not have scales, it has to be calibrated at:

— A point above the maximum expected reading;
— A point near the detection limit;
— A point near the expected routine operating region.

Instruments are calibrated with a specific cable and detector combination. The instrument, cable and detector combination need not be changed unless specifically documented by the instrument manual or calibration certificate.

Instruments used to perform calibrations, such as pulsers, voltmeters, etc., require calibration on an annual basis or more frequently if recommended by the

manufacturer's specifications. A technical basis is required for any instrument whose calibration is scheduled at a period greater than annually.

Equipment is marked to indicate calibration status. Equipment that is out of calibration is tagged or segregated until repaired, recalibrated or replaced.

Each instrument requires calibration, maintenance, functional checks, qualification for its intended use, and control charts to be developed for checking its ongoing performance. These documents are normally maintained in a folder for that particular instrument.

Test records need to be available for the instruments used in the planning stage and also any instruments used in the remediation process to determine when the end state has been reached. These need to be on record and need to demonstrate that the equipment complies with any relevant national laws and has clear traceability to national standards.

References [23–29] can be used to provide additional information on the development of a calibration programme.

V.1.3. Source certificates

Each instrument is checked with a source during operation at least daily or prior to use. In ratemeter mode, instruments typically exhibit a response within 20% of the expected reading when exposed to a source in a constant and reproducible manner. Once the instrument has been shown to respond within tolerance, it is permissible to obtain generic reference readings for a specific source. This is accomplished by collecting a statistically significant number of background readings and readings with the source. The average source reading and control limits can then be placed on a chart. Any future readings are then recorded on the chart and compared with the control limits, assuming that the background has not varied.

Any radioactive sources used in testing and calibration need to have some sort of traceability to national standards. For fundamental sources, this traceability needs to be quite direct and the uncertainties up to industry standards. For less fundamental sources, such as function check sources or test materials, a less formal approach is acceptable, with wider uncertainties, but the continued fitness for use has to be clear.

Sources used for instrument functional checks, including check sources, are maintained by a source inventory. Sources are tracked by radionuclide, activity and serial number, if applicable. Sources are stored only in approved locations. Instruments with affixed sources are also included in the source control programme.

Appendix VI

EXAMPLE OF A FINAL STATUS SURVEY CHECKLIST

VI.1. SURVEY PREPARATIONS

— The radionuclides of concern are identified. It is determined whether the radionuclides of concern exist in background. This will determine whether one-sample or two-sample tests are performed to demonstrate compliance. Two-sample tests are performed when radionuclides are present in the natural background; one-sample tests may be performed if the radionuclide is not present in background.
— It is ensured that residual radioactivity limits have been determined for the radionuclides present at the site, typically performed during earlier surveys associated with the remediation process.
— The site is segregated into sub-areas, based on the history of site usage, current and future exposure scenarios, and contamination potential.
— Applicable survey measurement units (Bq/g, cpm, cps, μSv/h, etc.) are identified.
— Representative reference (background) areas for both indoor and outdoor survey areas are selected. Such reference areas need to be selected from non-impacted areas and need to be:
  • Free of contamination from site operations;
  • Exhibit similar physical, chemical and biological characteristics as the survey area;
  • Have similar site usage but have no history of operations dealing with radioactive or contaminated materials.
— Appropriate survey instruments and survey techniques are selected. Applicable minimum MDCs are determined. Instrumentation is selected based on the ability to detect contamination at 10–50% of the derived concentration guideline limits for the radionuclide(s).
— Site areas are prepared for survey work as required (i.e. free and unrestricted access to all areas to be surveyed).
— A reference coordinate system is established for the site, as appropriate, based upon the system developed for the original cleanup work.

VI.2. PLANNING OF MONITORING

— The objective of monitoring is defined.
— Sample collection and analysis procedures are specified.
— The number of data points for statistical tests are determined, depending on whether or not the radionuclide is present in background.
— The number of samples/measurements to be obtained is specified based on the statistical tests.
— It is ensured that the sample size is sufficient for detecting areas of elevated activity.
— Additional samples/measurements are added for QC and QA.
— Sampling locations and frequency of collection are specified.
— Information on survey instrumentation and techniques are provided. The decision to use portable survey instrumentation or in situ techniques, and/or a combination of both, depends on whether or not the radiation levels are elevated compared to natural background, and whether or not the residual radioactivity is present at some fraction of background levels.
— Methods of data compilation are specified and survey units compared to reference areas.
— QC procedures are provided and a plan made for ensuring validity of the monitoring data:
  • Properly calibrated instrumentation;
  • Necessary replicate, reference and blank measurements.
— Field measurement results are compared to laboratory sample analyses.
— The survey plan is documented.

VI.3. CONDUCTING MONITORING

— Reference (background) area measurements and sampling are performed.
— Survey activities are conducted:
  • Surface scans of the different groups of areas are performed;
  • Surface activity measurements and sampling at previously selected sampling locations are conducted;
  • Additional direct measurements and sampling are conducted at locations based on professional judgement.
— Any necessary investigation activities are performed and documented, including survey unit reclassification, remediation and resurvey.
— Measurement and sample location are documented; information on measurement system MDC and measurement errors are provided.

— Any observations, abnormalities and deviations from the quality programme or standard operating procedures are documented.

VI.4. EVALUATING MONITORING RESULTS

— DQOs are reviewed.
— Samples are analysed.
— Data reduction on monitoring results are performed.
— Assumptions of statistical tests are verified.
— Survey results are compared with regulatory derived concentration limits.
— Elevated measurement comparisons are conducted.
— Area-weighted average is determined, if appropriate.
— Wilcoxon rank sum or sign tests are conducted.
— The final remediation report is prepared.
— An independent review of the report is obtained.

Appendix VII

RESPONSIBILITIES DURING FINAL REMEDIATION MONITORING

This appendix summarizes the principal responsibilities of major organizations involved in monitoring to release a site from regulatory control.

VII.1. REGULATORY BODY

In relation to the compliance monitoring for site release from regulatory control, the regulatory body may have the following general responsibilities:

— To ensure that the workers, the public and the environment are protected by establishing and implementing appropriate regulations, safety requirements and criteria for remediation and release of sites from regulatory control, and necessary control and enforcement mechanisms. This includes the establishment of generic site release criteria or procedures for review and approval of site specific release criteria proposed by licensees.
— To ensure that an appropriate and adequate monitoring strategy has been developed and implemented by the licensee (and its contractors) to demonstrate compliance with release criteria.
— To ensure through review and inspections that the licensees and, to the appropriate extent, the contractors, comply with the appropriate regulations and regulatory requirements including auditing such monitoring as may be necessary.
— To ensure independent review of the results from the final remediation monitoring before final decision on release of the site from regulatory control.
— To ensure involvement of interested parties and demonstrate that judgements regarding the safety of the public are based upon adequate and verified monitoring results.

In case of remediation activities at a contaminated site with no defined operator/owner, the regulatory body also needs to ensure:

— Identification of a responsible organization (State or private) that will develop and implement a monitoring strategy for compliance with release criteria;
— That a financial mechanism and resources are in place for performing remediation, monitoring activities and managing the wastes;

— Identification of a responsible organization for recording keeping and archiving the monitoring data, procedures and results;
— Coordination of all competent authorities involved in the monitoring up to final release of the site from regulatory control.

VII.2. THE LICENSEE OR OTHER ORGANIZATION DESIGNATED BY THE REGULATORY BODY

The licensee or other designated authority:

— Develops a monitoring strategy for approval by the regulatory body;
— Ensures necessary equipment, personnel, programmes and financial resources are provided to implement the remediation and monitoring programmes;
— Implements the remediation and monitoring in accordance with the approved strategy;
— Complies with applicable regulatory requirements;
— Provides periodic reports of progress to the regulatory body;
— Promptly notifies the regulatory body of incidents, occurrences and unanticipated findings that may adversely impact the project schedule, cost or compliance with established criteria;
— Prepares a report, describing the results of the compliance monitoring, and submits the request to the regulatory body.

VII.3. OTHER COMPETENT AUTHORITIES

The government or the regulatory body may delegate specific responsibilities to other governmental agencies, in particular when remediation is required at a site with an unknown owner or if the licence holder does not have the resources and capabilities to perform the monitoring activities. The government may control this delegation through the regulatory body or through delegation of authorities to other competent authorities. The delegation may concern:

— Review, testing, calibration of monitoring equipment;
— Review of the QA programme;
— Review of staff competency;
— Independent review and verification of monitoring results;

— Physical protection of the site and implementation of other institutional measures;
— Design and regular performance of the confirmatory programmes of measurements to verify the quality of the results provided by the licensee;
— Collection and retention of data provided by licensees, governmental or international agencies;
— Establishing standards for non-radiological contamination (e.g. water, soil quality).

Appendix VIII

EXAMPLE OF AN INTEGRATED WORK PERMIT

INTEGRATED WORK PERMIT

(A) WORK DESCRIPTION: WORK PACKAGE NUMBER/APPLICABLE PROCEDURES:	(B) WORK LOCATION: Permit # (C) START DATE: EXPIRATION DATE: (D) REQUESTED BY: REQUEST DATE: (E) RADIOLOGICAL AND SAFETY/INDUSTRIAL HYGIENE SURVEYS
(F) HAZARDOUS CONDITIONS	TYPE: NUMBER: DATE: BY:
CHEMICALS:	

(G) REQUIRED PERSONNEL PROTECTIVE CLOTHING AND EQUIPMENT

HEAD/EYES	FEET	HANDS	BODY	RESPIRATORY
SAFETY GLASSES ☐	RUBBER BOOTS ☐	COTTON GLOVES ☐	COVERALL/COTTON ☐	FULL-FACE NEGATIVE PRESSURE RESPIRATOR: ☐
GOGGLES ☐	PLASTIC BOOTS ☐	PLAYTEX GLOVES ☐	COVERALL/TYVEX	POWERED AIR PURIFIER: ☐
FACE SHIELD ☐	HIP WADERS ☐	RUBBER GLOVES ☐	APRON ☐	CARTRIDGE TYPE: _____
HARD HAT ☐	STEEL-TOED SHOES ☐	NEOPRENE GLOVES ☐	FALL ARRESTOR ☐	SUPPLIED AIR HOOD ☐
EAR PROTECTION ☐	DISPOSABLE SHOE COVERS ☐	SURGICAL GLOVES ☐	RUBBER SUIT ☐	SANDBLAST HOOD ☐
		LEATHER GLOVES ☐	RAIN SUIT ☐	SELF CONTAINED BREATHING APPARATUS ☐
		OTHER GLOVES ☐	TAPED OPENINGS ☐	

(H) ADDITIONAL PERMITS/PRECAUTIONS

EXCAVATION PERMIT ☐
CONFINED SPACE PERMIT ☐
FALL PROTECTION PLAN ☐
HOT WORK PERMIT ☐
ENERGIZED SYSTEM LOCKOUT ☐
HOISTING/RIGGING ☐
PRE-ENTRY MONITORING ☐
CONTINUOUS MONITORING ☐
HEAT/COLD STRESS MONITORING ☐
NOISE MONITORING ☐
'BUDDY SYSTEM' IN EFFECT ☐
JOB COVERAGE BY ENVIRONMENTAL SAFETY AND HEALTH & QUALITY ASSURANCE ☐
WATCHMAN/LOOKOUT/FLAGGER ☐
GUARDS/BARRIERS ☐
EMERGENCY/RESCUE EQUIPMENT ☐
LADDERS/SCAFFOLDS ☐
PERSONNEL LIFTING DEVICES ☐
GRINDING, ABRASIVE WHEELS ☐
POWERED TOOLS ☐
VENTILATION UNITS ☐

(I) TRAININGS

GENERAL EMPLOYEE TRAINING ☐
General Employee Radiation Training ☐
Radiation Worker ☐
SPECIAL TRAINING (SPECIFY): ---------- ☐

(J) RADIOLOGICAL MONITORING

TLD BADGE:
EXTREMITY TLD:
SRD 0–200 mSv:
BIOASSAY
MONTHLY ☐ QUATERLY ☐
6-MONTHLY ☐ ANNUAL ☐

Notes: Additional comments:

(K) INDUSTRIAL HYGIENE MONITORING — INDIVIDUAL — GROUP

(L) PERMIT TERMINATION

REASON FOR TERMINATING THIS HAZARDOUS WORK PERMIT:

NUMBER OF SIGN IN ROSTERS ATTACHED:

REPLACEMENT HAZARDOUS WORK PERMIT NUMBER:

APPROVALS: DATE	TERMINATION: DATE
ENVIRONMENTAL, SAFETY AND HEALTH & QUALITY ASSURANCE MANAGER:	ENVIRONMENTAL, SAFETY AND HEALTH & QUALITY ASSURANCE MANAGER:
RADCON MANAGER:	RADCON MANAGER:
FIELD SERVICES MANAGER:	FIELD SERVICES MANAGER:

Appendix IX

DETECTION AND QUANTIFICATION CAPABILITIES

The detection capability of a measurement system refers to a radiation level or quantity of radioactive material that can be detected or quantified with some known or estimated level of confidence. This quantity is a factor of both the instrumentation and the measurement technique, and is commonly referred to as the minimum detectable concentration (MDC). During planning of monitoring, it is generally considered good practice to select a measurement instrument and/or technique that has a capability in the range of 10–50% of the release criterion of concern. Sometimes, this goal may not be achievable because of site specific conditions and circumstances (e.g. ambient background levels, low release criteria, cost restrictions and available technology). In cases where integrating instruments are used, for example, in laboratory counting facilities, the term 'minimum detectable activity' (MDA) is normally used.

The primary parameters that affect the detection capability of a radiation detector are the background count rate, detection efficiency and the counting time interval. It is important to use actual background count rate values and detection efficiencies when determining counting and scanning parameters, particularly during final status and verification surveys. When making field measurements, the detection capability will usually be less than what can be achieved in a laboratory due to increased background and often significantly lower detection efficiency. It is often impossible to guarantee that pure alpha emitters can be detected in situ since the weathering of aged surfaces will often completely absorb the alpha emissions.

Prior to performing field measurements, an investigator must evaluate the detection capability of the equipment proposed for use to ensure that levels below the release criteria can be detected. After a direct measurement has been made, it is then necessary to determine whether or not the result can be distinguished from the instrument background response of the measurement system. The terms that are used in this Safety Report to define detection capability for fixed point counts and sample analyses are:

— Critical level (L_C);
— Detection limit (L_D);
— MDA;
— MDC.

L_C is the level, in counts, at which there is a statistical probability (with a predetermined confidence) of incorrectly identifying a measurement system

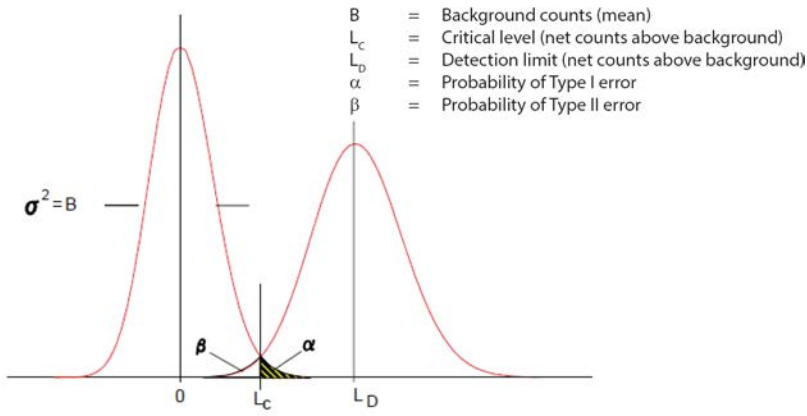

FIG. 50. Graphical representation of probabilities for Type I and II errors in detection capability for instrumentation with a background response.

background value as 'greater than background'. Any response above this level is considered to be greater than background. L_D is an a priori estimate of the detection capability of a measurement system and is also reported in units of counts. MDA is the detection limit (counts) multiplied by an appropriate conversion factor to give units consistent with a site guideline, such as becquerels. When the activity is described in units of space or mass, the term becomes MDC and is expressed in becquerels per kilogram, for instance.

The two parameters of interest for a detector system with a background response greater than zero are:

(a) L_C: the net response level, in counts, at which the detector output can be considered 'above background'.
(b) L_D: the net response level, in counts that can be expected to be seen with a detector with a fixed level of certainty.

Assuming that a system has a background response and that random uncertainties and systematic uncertainties are accounted for separately, these parameters can be calculated using Poisson statistics. For these calculations, two types of decision errors need to be considered. A Type II error (or 'false negative') occurs when a detector response is considered to be background when in fact radiation is present at levels above background. The probability of a Type I error is referred to as α and is associated with L_C; the probability of a Type II error is referred to as β and is associated with L_D. Figure 50 graphically illustrates the relationship of these terms with respect to each other and to a normal background distribution.

If α and β are assumed to be equal, the variance (σ^2) of all measurement values is assumed to be equal to the values themselves. If the background of the detection system is not well known, then the critical detection level and the detection limit can be calculated by using the following formulae:

$$L_C = k\sqrt{2B}$$
$$L_D = k^2 + 2k\sqrt{2B} \quad (16)$$

where

L_C is the critical level (counts);
L_D is the detection limit (counts);
k is the Poisson probability sum for α and β (assuming α and β are equal);

and B is the number of background counts that are expected to occur while performing an actual measurement.

The curve to the left in the diagram is the background distribution minus the mean of the background distribution. The result is a Poisson distribution with a mean equal to zero and a variance, σ^2, equal to B. It should be noted that the distribution only accounts for the expected statistical variation due to the stochastic nature of radioactive decay. Currie assumed 'paired blanks' when deriving the above stated relationships, which is interpreted to mean that the sample and background count times are the same.

If values of 0.05 for both α and β are selected as being acceptable, then $k = 1.645$ and the equations can be written as:

$$L_C = 2.33B^{1/2}$$
$$L_D = 2.71 + 4.65B^{1/2} \quad (17)$$

Continuing in this manner, MDA is defined as the smallest amount or concentration of radioactive material that will yield a net positive count with a 5% probability of falsely interpreting background responses as true activity from contamination. Two different MDCs are of concern for field measurements — one for direct surface activity measurement (MDC_{static}) and one for scanning of surfaces to identify areas of residual activity (MDC_{scan}). These two MDCs are calculated differently. The equation used for calculating the MDC_{static} for direct measurements is as follows:

$$\mathrm{MDC}_{\mathrm{static}} = \frac{\dfrac{2.71}{t_s} + 3.29\sqrt{\dfrac{R_b}{t_s} + \dfrac{R_b}{t_b}}}{C\varepsilon_i\varepsilon_s\left(\dfrac{A}{100}\right)} \tag{18}$$

where

$\mathrm{MDC}_{\mathrm{static}}$ is minimum detectable concentration (dpm/100 cm^2, etc.);
R_b is background count rate (cpm);
t_b is background count time (min);
t_s is sample count time (min);
ε_i is instrument efficiency;
ε_s is surface efficiency;
A is detector area (cm^2);

and C corresponds to constants for converting to desired units of activity.

The ability to identify a small area of elevated radioactivity during surface scanning is dependent upon the surveyor's skill in recognizing an increase in the audible or display output of an instrument. For notation purposes, the term 'scanning capability' is used throughout this section to describe the ability of a surveyor to detect a predetermined level of contamination with a detector. The probability of detecting residual contamination in the field depends not only on the capability of the monitoring instrumentation when used in the scanning mode of operation, but is also affected by the surveyor's ability — i.e. human factors. The surveyor must make a decision as to whether the signals represent only the background activity or residual contamination in excess of background. The greater the capability is, the lower the level of contamination that may be detected by scanning. Accounting for these human factors represents a significant change from the traditionally accepted methods of estimating scanning sensitivities.

The equation used to calculate the $\mathrm{MDC}_{\mathrm{scan}}$ for surfaces is as follows:

$$\mathrm{MDC}_{\mathrm{scan}} = \frac{d'\sqrt{b_i}\,\dfrac{60}{i}}{\varepsilon_i\varepsilon_s\sqrt{p}\,\dfrac{A}{100}C} \tag{19}$$

where

MDC_{scan} is the minimum detectable concentration (dpm/100 cm^2, Bg/cm^2, etc.);
d' is the decision error taken from table 6-5 of MARSSIM [9] (typically 1.38);
i is the observation counting interval (scan speed divided by the detector width);
b_i is background count per observation interval;
ε_i is detector efficiency;
ε_s is surface efficiency;
p is surveyor efficiency from MARSSIM [9] (typically 0.5);
A is detector area (cm^2);

and C corresponds to constants for converting to desired units of activity.

Scanning for alpha emitters differs from scanning for beta and gamma emitters in that the expected background response of most alpha detectors is very close to zero. The following discussion covers scanning for alpha emitters and assumes that the surface being monitored is similar in nature to the material on which the detector was calibrated. In this respect, the approach is purely theoretical. Monitoring surfaces that are dirty, non-planar or weathered can significantly affect the detection efficiency and, therefore, bias the expected MDC for the scan. The use of reasonable detection efficiency values instead of optimistic values is highly recommended.

Since the time a contaminated area is under the probe varies and the background count rate of some alpha instruments is less than 1 cpm, it is not practical to determine a fixed MDC for scanning. Instead, it is more useful to determine the probability of detecting an area of contamination at a predetermined release criterion level for given scan rates.

For alpha monitoring instrumentation with backgrounds ranging from <1 to 3 cpm, a single count provides a surveyor sufficient cause to stop and investigate further. Assuming this to be true, the probability of detecting given levels of alpha surface contamination can be calculated by use of Poisson summation statistics.

Given a known scan rate and a surface contamination criterion, the probability of detecting a single count while passing over the contaminated area is:

$$P(n \geq 1) = 1 - \exp\left(-\frac{GEd}{60v}\right) \tag{20}$$

where

G is contamination activity (dpm);
E is detection efficiency (total);
d is width of detector in direction of scan (cm);

and v is scan speed (cm/s).

Once a count is recorded, the surveyor needs to stop and wait until the probability of getting another count is at least 90%. This time interval can be calculated by:

$$t = \frac{13.800}{CAE} \tag{21}$$

where

t is the time period for static count (s);
C is the contamination guideline (dpm/100 cm^2);
A is physical probe area (cm^2);

and E is detector efficiency.

Many portable proportional counters have background count rates on the order of 5–10 cpm, and a single count does not have to cause a surveyor to investigate further. A counting period long enough to establish that a single count indicates an elevated contamination level would be prohibitively inefficient. For these types of instruments, the surveyor usually needs to get at least two counts while passing over the source area before stopping for further investigation.

Assuming this to be a valid assumption, the probability of getting two or more counts can be calculated by:

$$\begin{aligned} P(n \geq 2) &= 1 - P(n = 0) - P(n = 1) \\ &= 1 - \left(1 + \frac{(GE + B)t}{60}\right) \exp\left(-\frac{(GE + B)t}{60}\right) \end{aligned} \tag{22}$$

where

$P(n \geq 2)$ is the probability of getting two or more counts during the time interval t;
$P(n = 0)$ is the probability of not getting any counts during the time interval t;
$P(n = 1)$ is the probability of getting one count during the time interval t;

and B is background count rate (cpm).

All other variables are the same as used in the above equation for detecting a simple event.

For laboratory analysis, the MDA is calculated similarly to the MDC_{static} determination described above. Several modifications to the equation are necessary for analysis-specific parameters including chemical recovery, sample mass and abundance of the measured radiation per radionuclide decay.

$$\mathrm{MDA} = \frac{\dfrac{2.71}{t_s} + 3.29\sqrt{\dfrac{R_b}{t_s} + \dfrac{R_b}{t_b}}}{W \times \mathrm{Rec} \times C \times E \times f} \tag{23}$$

where

MDA is minimum detectable activity (ph/g, Bq/kg, etc.);
R_b is background count rate (cpm);
t_b is background count time (min);
t_s is sample count time (min);
W is sample mass;
Rec is chemical recovery of method;
f is abundance for decay;
E is efficiency of the counting system;

and C corresponds to constants for converting to derived units of activity.

Appendix X

EXAMPLE OF A PROCEDURE FOR DETERMINATION OF REMOVABLE ACTIVITY

X.1. INTRODUCTION

Purpose: This procedure provides instructions on taking measurements of removable activity using an indirect swipe.

Scope: This procedure addresses the actions, equipment, tools and personnel necessary to obtain a sample to determine whether loose surface contamination exists.

Applicability: This procedure is used when performing surveys of items to determine whether removable surface contamination is present.

X.2. PRECAUTIONS AND LIMITATIONS

Care must be taken to avoid sharp edges or moving parts (e.g. engine fans) when reaching around or into objects being surveyed.

X.3. PREREQUISITE ACTIONS

Training/qualification requirements

It is important that personnel performing this procedure have the training and experience needed to operate radiological survey equipment, and the training required by the health and safety plan. Examples of qualified individuals include, but are not limited to, health physicists, industrial hygienists, radiation protection and industrial hygiene technicians, laboratory technicians and field monitors. Documentation of personnel qualifications (i.e. résumés, organizational training and qualification records) are maintained in accordance with the quality plan.

Health and safety briefing requirements

This procedure, along with performance documents or forms prior to performing this activity, are received and reviewed. The supervisor is contacted with any questions regarding performance of the procedure.

Performance documents

The appropriate procedure is used for the operation of the specific instrument that is used to survey the area. The site document control log is reviewed to determine the most recent revision of procedures and documents.

Required forms

Records forms (e.g. SF-xx1, SF-xx2, SF-xx3) — swipe location and results of surveys are recorded.

Special tools, equipment, parts and supplies

Based on the type of measurements to be taken, this may include:

— Filter paper (2 in), numbered.
— A glassine envelope or bag to hold the filter.
— Ludlum Model 3030 (2929) or equivalent meter to measure alpha and beta/gamma contamination.
— Check sources (^{230}Th, ^{90}Sr).
— Disposable gloves (typically latex or nitrile).
— Identifying the location of swipes on a drawing of the area. The swipes are assigned a number and list on the survey form.

Approvals and notifications

— Prior to performing surveys, it is ensured that the facility representative is aware of the work that is to be performed.
— The radiation safety officer is notified if swipe results are greater than four times background or a value determined by the programme.

X.4. DETERMINATION OF REMOVABLE ACTIVITY

Sample collection: It is important to note that if direct measurement surveys of an area will also be completed, there is a need to perform the direct measurements of the surface before a swipe sample is taken (annotated on the survey form):

(a) A representative surface that is flat, smooth and stationary is selected, if possible.

(b) One side of all filter papers is marked with an ‘x’.
(c) With two gloved fingers, moderate pressure is applied to the unmarked side of the filter paper over the area to be surveyed. The survey surface needs to be approximately 100 cm^2 or 10 cm × 10 cm.
(d) The Ludlum Model 3030 operations procedure is referred to for performing the QA/QC routine prior to counting of filter paper swipes.
(e) The amount of radioactive material on the filter paper is determined by placing the filter paper onto a planchet, which is placed inside the Ludlum Model 3030.
(f) The filter paper is counted for 1 min (or longer if directed by a health physicist) according to the manufacturer’s instructions.
(g) For alpha activity levels greater than 20 dpm/100 cm^2, the health physicist is notified of the filter paper results. This information is recorded on the appropriate form and survey map.
(h) For beta/gamma activity levels greater than 1000 dpm/100 cm^2, the health physicist is notified of the filter paper results. This information is recorded on the appropriate form and survey map. It should be noted that it is necessary to wait for 30 min and count again. If the filter paper count rate decreases by approximately half, then the radioactivity may be due to radon and its progeny. If the count rate does not decrease, then the radioactivity is due to other alpha or beta activity. This indicates that a radioactive loose surface contamination condition exists. The results are reported to the health physicist.
(i) The filter is placed into a glassine envelope. Care should be taken not to shake off collected material from the filter paper.
(j) The swipe number, swipe location, date, time, collector’s name and location (GPS coordinates if available) are recorded on the envelope.
(k) The swipe survey results are recorded on the survey form. It should be noted that it is necessary to use caution when handling swipes with an activity greater than 20 dpm/100 cm^2 alpha or 1000 dpm/100 cm^2 beta/gamma, because of the possibility of contaminating counting equipment.
(l) The sample is returned to the originator, or if written directions authorize, disposed of as low specific activity waste.

Appendix XI

EXAMPLE OF A CHAIN OF CUSTODY RECORD

CHAIN-OF-CUSTODY RECORD

COC Number:
Purchase Order Number:

Lab Destination:	Lab Receiving Address:	Analysis Desired
Project Name	Sample Location:	
Project Number:		
Client Rep:	Project Manager:	

Item No.	Sample Number	Date	Time	Comp	Grab	Sample Description	Number of Containers										
1																	
2																	
3																	
4																	
5																	
6																	
7																	
8																	

Turnaround Time Required (Calendar Days):		Sampled By:	Purchase Order No.:	Laboratory R

Transfer Number	Transfers Relinquished By	Date	Time	Transfers Accepted By	Date	Time	Remarks
1							
2							
3							*** Fax results to:
4							

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