Safety Reports Series
No. 67

Monitoring for Compliance with Exemption and Clearance Levels

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MONITORING FOR COMPLIANCE WITH EXEMPTION AND CLEARANCE LEVELS

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MONITORING FOR COMPLIANCE WITH EXEMPTION AND CLEARANCE LEVELS

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FOREWORD

Radioactive material is present in the environment and is also generated during the operation and subsequent decommissioning of facilities that have used or produced radioactive material. Particularly during the decommissioning process, it is generally expected that a large amount of the material will be below the activity limits requiring regulatory control, and, therefore, could be released for further use.

The concepts of exclusion, exemption and clearance from regulatory control for radioactive material are defined and explained in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources. Over the last decade, IAEA Member States have made considerable efforts to develop consensus on the application of these concepts. Significantly, however, Member States have achieved international consensus on activity concentration values for radioactive material of natural and artificial origin below which regulatory control is not required. Agreement on this topic is documented in IAEA Safety Standards Series No. RS-G-1.7, Application of the Concepts of Exclusion, Exemption and Clearance. During the development of this Safety Guide, Member States highlighted the need for further recommendations by the IAEA on the use and application, in practice, of activity concentration values for instances in which various types of material (e.g. metal, concrete, wood) with different types and levels of contamination require consideration for release from regulatory control.

This Safety Report was developed to provide practical examples to operating organizations, regulatory bodies, and other organizations and experts that are involved in the monitoring of material for releasing it from regulatory control. It focuses on the development and practical implementation of strategies for demonstrating compliance with the established levels.

The IAEA expresses its gratitude to all experts who participated in the development and review of this publication. The IAEA officers responsible for this publication were B. Batandjieva and V. Ljubenov of the Division of Radiation, Transport and Waste Safety.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Many uses of radioactive material are beneficial to mankind, for example in industry, research, medical diagnosis and cancer treatment. However, radioactive material can also be potentially harmful to public health and the environment, and its use is, therefore, controlled. The internationally accepted approach to regulation of radioactive material is based on a system of notification and authorization, as described in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [1].

The BSS [1] establishes the requirements for the protection of workers, the public and the environment against the risks associated with radiation exposure. It also defines and explains the use of the concepts of exclusion[1], exemption[2] and clearance[3] for establishing the scope of regulatory control of moderate[4] quantities of material. The IAEA issued complementary guidance [2] on the application of these three concepts to bulk material. These concepts are extremely important when concerned with decommissioning of facilities[5], where large quantities of material can potentially be released from regulatory control.

During the operation of facilities, certain areas are controlled for potential radiological hazards. Many of these areas and the equipment/materials in them are neither irradiated nor contaminated during the period of operation. Some

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[1] The term 'exclusion' means the deliberate exclusion of a particular category of exposure from the scope of an instrument of regulatory control on the grounds that it is not considered amenable to control through the regulatory instrument in question. Such exposure is termed excluded exposure [2].

[2] The term 'exemption' means the determination by a regulatory body that a source or practice need not be subject to some or all aspects of regulatory control on the basis that the exposure (including potential exposure) due to the source or practice is too small to warrant the application of those aspects [2].

[3] The term 'clearance' means the removal of radioactive materials or radioactive objects within authorized practices from any further regulatory control by the regulatory body. Removal from control in this context refers to control applied for radiation protection purposes [2].

[4] The term 'moderate quantities' means quantities that "are at most of the order of a tonne" of material. Anything greater than this amount is considered 'bulk quantities' [1].

[5] The term 'facility' means a facility with its associated land, buildings and equipment in which radioactive material is used, processed, handled or stored on such a scale that consideration of safety is required [3].

material and equipment is lightly contaminated and easily cleaned. Some high value material may become contaminated and, due to the value, undergoes lengthy and detailed decontamination efforts. These materials are removed prior to and during decommissioning. Based on technical evaluation, these materials may be exempted or cleared from regulatory control.

Decommissioning of nuclear reactors and other facilities generates large quantities of material that can be removed from regulatory control. For example, the quantity of concrete from the 58 MW(e) MZFR research reactor in Germany (being decommissioned) amounts to about 42 000 t, while the larger decommissioned 106 MW(e) KKN power reactor had about 70 000 t. The building mass of a typical nuclear power plant with a 1000 MW(e) light water reactor will amount to 150 000–200 000 t [3]. Although some of this material can be released with little or no monitoring, other specific quantities may require more extensive monitoring and evaluation.

It is important to realize that the application of exclusion, exemption and clearance concepts covers not only decommissioning activities but is also related to a large range of operational activities in practice[6] situations. Different approaches to the application of the concepts of exclusion, exemption and clearance are used by different Member States. However, international consensus has been achieved on activity concentration values (Bq/g) below which material does not require regulatory control [2].

The practical implementation of these levels needs to consider a graded approach and take into account the size of the project (e.g. nuclear power plant versus research laboratory), the national regulatory framework and general economic factors. Regardless of the size of the project, adequate monitoring of the material to be released is required to demonstrate that the requirements of the regulatory body are met.

1.2. OBJECTIVE

The objective of this publication is to provide practical information on the application of the exemption and clearance levels, and the activities required for the demonstration of compliance with these levels. The levels generally referred to in this Safety Report are those established in Ref. [2]. However, the concepts

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[6] ‘Practice’ is any human activity that introduces additional sources of exposure or exposure pathways or extends exposure to additional people or modifies the network of exposure pathways from existing sources, so as to increase the exposure or the likelihood of exposure of people or the number of people exposed [1].

and techniques discussed would also apply to other specific criteria, established by the national regulatory bodies.

This Safety Report aims to assist operators and technical support organizations in planning, performing and assessing the results of monitoring of material considered for release from regulatory control, with subsequent validation of compliance with established levels. It is also meant to be useful for regulators when verifying whether a monitoring strategy is appropriately defined and implemented to demonstrate compliance with the established levels.

1.3. SCOPE

This Safety Report covers the development and implementation of strategies for monitoring for compliance with exemption or clearance of material containing low activity concentrations of radionuclides originating from authorized practices, which include both operating and decommissioning activities for all types of facilities. It also provides recommendations on the selection of monitoring instrumentation and techniques, illustrated through a series of practical examples.

Reference [2] — Application of the Concepts of Exclusion, Exemption and Clearance — considers activity concentrations as a means of determining suitability of a material for exemption and clearance. Some Member States choose to use surface contamination values as reference levels for exemption and clearance. Measurement of surface contamination may be necessary to determine the activity concentration of the material to be considered, but the levels recommended by the IAEA are described as concentration values. This implies that the volume over which the contamination is averaged is critical in determining the activity concentration of the radionuclide in the material. Specific examples for application of this approach are found in the appendices.

The present publication does not cover intervention[7] situations. However, it could be applied for monitoring when releasing material other than land from regulatory control during remediation of sites because these activities are considered as a practice. The monitoring of land is not addressed in this publication as it is addressed in Ref. [4]. It also does not address activity concentrations for foodstuffs, drinking water or animal feed, as there are specific values provided in Refs [5, 6]. The Safety Report does not apply to radon in air,

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[7] ‘Intervention’ is defined as any action intended to reduce or avert exposure or the likelihood of exposure to sources which are not part of a controlled practice or which are out of control as a consequence of an accident [1].

as action levels are provided in Ref. [1]; ^{40}K in the body (excluded from Ref. [1]); and material in transport in accordance with the IAEA Transport Regulations [7]. This Safety Report does consider radionuclides and their progeny, such as ^{137m}Ba in the decay of ^{137}Cs, and this is indicated by ^{137}Cs + d.

1.4. STRUCTURE

Section 1 of this Safety Report provides the background, objective, scope and structure of this report. The general approach and necessary steps for selection of an optimum strategy for monitoring for compliance are discussed in Section 2. The selection of monitoring techniques and instruments that could be applied to specific situations is described in Section 3. The challenges of monitoring for compliance are discussed in Section 4, and activities for evaluation of data and confidence building in monitoring results in Section 5. Necessary measures for quality management are addressed in Section 6. Practical examples of strategies on monitoring for compliance and their implementation in realistic situations are illustrated in the appendices to this Safety Report.

2. GENERAL APPROACH

The monitoring process for compliance with exemption and clearance levels (referred to as monitoring throughout the text) is complex and can involve time consuming procedures compared with routine operational radiation monitoring at facilities. For instance, clearance levels tend to be near the limit of detection capability for field instruments and large quantities of material may be involved. The process starts from the specification of the material to be considered for release and ends in follow-up actions arising from the monitoring results. The main steps of the monitoring process for compliance are presented in Fig. 1 and discussed in the following sections of this Safety Report.

It is important that, at the beginning of the monitoring process, the material to be monitored is properly defined and controlled (Section 2.1), and the levels for compliance purposes are established (Section 2.2). Next, a detailed history of candidate material for clearance needs to be collected (Section 2.3), theoretical estimates of the activity determined, and the characteristics and possible contamination levels described (Section 2.4). The management approach for

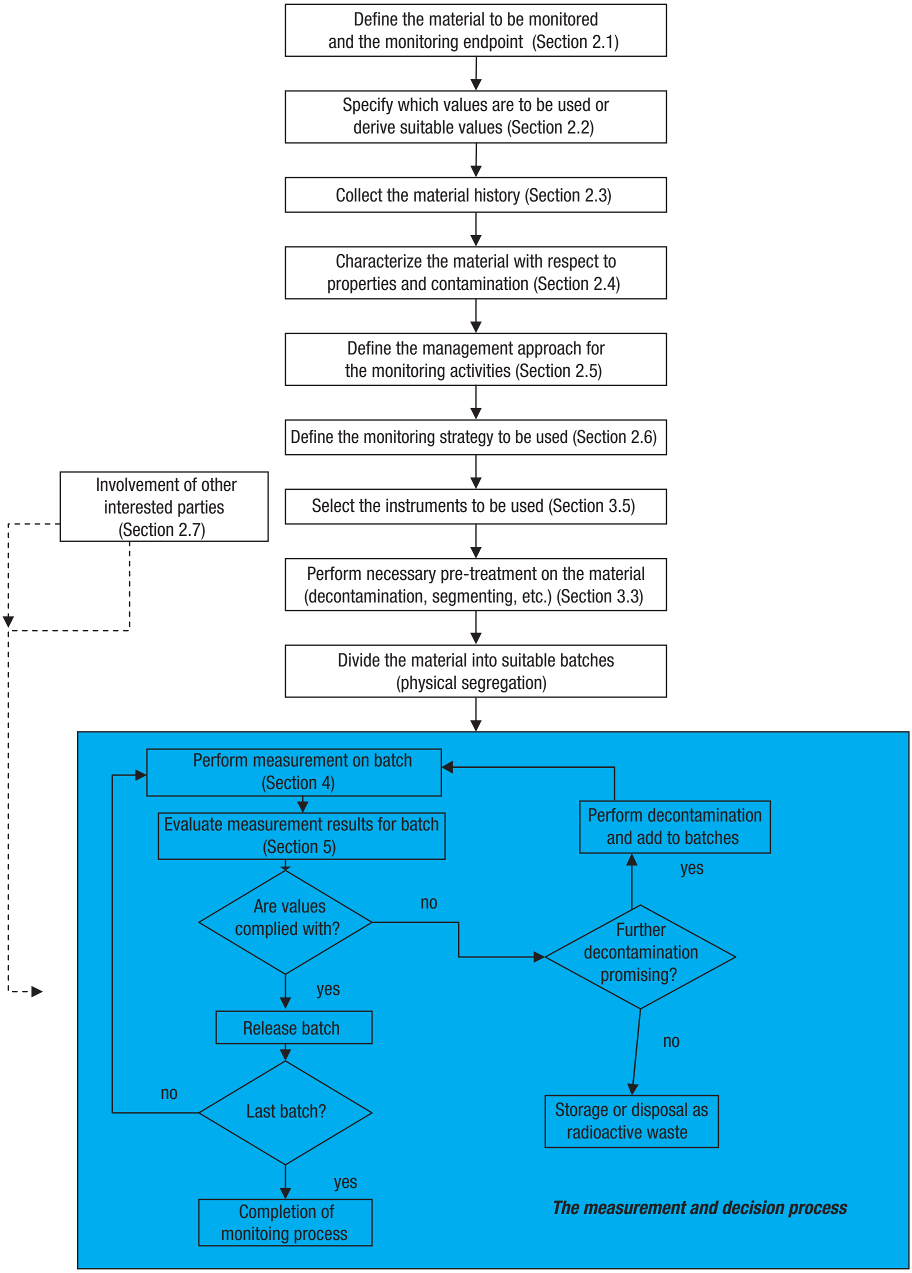

FIG. 1. Graphical presentation of the main steps of monitoring for compliance.

monitoring is defined to perform release of material effectively and efficiently (Section 2.5). The optimum monitoring strategy is defined based on the collected information (Section 2.6). Other interested parties need to be involved before release of the material from regulatory control (Section 2.7).

Instrumentation and techniques need to be specified (Section 3) in order to perform monitoring. The monitoring can present certain challenges that require resolution (Section 4). Evaluation and interpretation of monitoring results (Section 5) need to be performed, and then a description of follow-up actions is documented. Elements of a quality management programme that apply to this type of activity are discussed in Section 6.

2.1. DEFINITION OF MATERIAL AND MONITORING TASK

To establish a reliable and efficient monitoring process, it is necessary, at the beginning, to clearly define the material and the monitoring task to be performed. To adequately achieve this, the following information is needed:

- Goal of monitoring: exemption or clearance of material.
- Site location (e.g. boundaries of the site property, level of natural background).
- Type of facility (e.g. nuclear reactor, nuclear fuel fabrication plant, radioisotope production facility, hospital, etc.) and radionuclides associated with operations.
- Size, type and quantities of material (e.g. concrete, metal, plastic, rubble, paper).
- Expected levels of contamination or activation of each type of material through process knowledge or theoretical estimates.
- Other hazards associated with the material (e.g. biohazard, chemical, physical).
- Time frame for monitoring (e.g. monitoring throughput).

A systematic approach to the development of project goals, in this case, monitoring of equipment and materials for exemption or clearance, can be described using the data quality objective process [8].

2.2. EXCLUSION, EXEMPTION AND CLEARANCE LEVELS

Exclusion, exemption and clearance of material are based on compliance with levels established by the regulatory body. Some of these could be site specific, developed by the operator and approved by the regulatory body in accordance with the radiation protection criteria and authorization conditions. Alternatively, they could be generic, established by the regulatory body or adapted from international recommendations (e.g. Ref. [2]).

2.2.1. Principles of exclusion, exemption and clearance

Dose limitation applies to the exposure of workers and members of the public from all practices subject to control through the requirements of the BSS [1]. Therefore, the dose limit (1 mSv in a year) for members of the public represents an upper bound on the sum of doses from all possible combinations of exposures from authorized practices.

The levels for exclusion of material from regulatory control are based on any exposure whose magnitude or likelihood is essentially not amenable to control through the requirements of the standards (Ref. [1], para. 1.4).

The levels for exemption of material are related to a practice or a source within a practice. The exemption of material needs to ensure that "the effective dose expected to be incurred by any member of the public due to the exempted practice or source is of the order of 10 μSv or less in a year and either the collective committed effective dose by one year of performance of the practice is no more than about 1 man·Sv or an assessment for the optimization of protection shows that exemption is the optimum option" [1].

Clearance of material applies to release of material from an authorized practice that is subject to regulatory control. The BSS [1] states that "clearance levels shall take account of the exemption levels" and "shall not be higher than the exemption levels specified in Schedule I" of the BSS [1] or "unless otherwise approved by the Regulatory Authority." (Ref. [1], para. 2.19).

For bulk material, the BSS [1] defines the radiological criteria, which serve as a basis for the derivation of international generic values for activity concentrations [2] to be considered for the exclusion, exemption or clearance of bulk material.

The clearance and exemption levels are generally derived for every radionuclide and determined from the most significant exposure pathway for dose assessment. For mixtures of radionuclides, this implies that an additional safety margin is involved, i.e:

(a) For mixtures of radionuclides of natural origin, the concentration of each radionuclide needs to be below the relevant value of activity concentration given in Table 1 of Ref. [2], para. 4.6;

(b) For material containing a mixture of radionuclides of artificial origin, the sum of the fractions rule in Eq. (1) is applied:

$$\sum_{i=1}^{n} \frac{C_i}{(\text{clearance activity concentration for specific radionuclde})_i} \leq 1 \qquad (1)$$

where C_i is the concentration (Bq/g) of the ith radionuclide of artificial origin in the material, $(\text{activity concentration})_i$ is the value of the maximum allowable activity concentration for the radionuclide i in the material, and n is the number of radionuclides present (Ref. [2], para. 4.7). To ensure that the sum is not >1 requires the consideration of some rare cases in which scenarios with different radionuclides occur simultaneously.

For mixtures of both radionuclides of natural and artificial origin, both of the above mentioned rules need to be satisfied (Ref. [2], para. 4.8).

2.2.2. Generic and site specific activity concentration values

There is international agreement on generic values of activity concentrations that can be used by regulatory bodies for determining when controls over bulk amounts of material are not required or are no longer necessary [2]. These values are defined in terms of radionuclide concentration in Bq/g, which can be used as generic values for release of material from authorized practices, i.e. for determining whether regulatory control can be removed. Two approaches were used for the derivation of these values:

(a) The values for naturally occurring radionuclides were based on the upper end of the worldwide distribution of activity concentrations in soil provided by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [8].
(b) The values for radionuclides of artificial origin were established on the basis that the exposures would be of the order of 10 μSv in a year. These values for activity concentrations are shown in Appendix I, and specific details on the approach for derivation of the values are presented in Refs [2, 9].

Regulatory bodies have the authority and responsibility to adopt international guidance, or to define national generic values or require site specific values for release of bulk material from regulatory control. If the site specific approach is selected, the operators need to derive and justify the values, which will then be reviewed and approved by the regulatory body. In some cases, the operator will need to discuss the proposed values with other interested parties involved in the exemption or clearance. This issue is described in more detail in Section 2.7.

When establishing exemption or clearance levels, regulatory bodies need to be aware of other regulatory requirements that could also apply, such as requirements for transport and environmental limits and, to the extent possible, harmonize these requirements.

2.2.3. Graded approach

Consistent with the principles of optimization, the graded approach could be applied to clearance of materials that have a wide range of physical characteristics (such as solubility, density, and diffusion constants) and chemical characteristics, or materials that slightly exceed the established activity concentration values.

The application of the graded approach will generally depend on the homogeneity of the material, volume of the material, complexity of the material, and type and level of contamination. Limited resources could also necessitate the use of this approach. The graded approach may be implemented in various ways, for example, by applying a simplified monitoring procedure (e.g. scope, resources, number of samples; see Appendix II), or by performing different types of monitoring (scoping, characterization and monitoring surveys). Process knowledge is important in determining the application of the graded approach; the more one knows about the material, its use and history, its potential for contamination and its ultimate disposition, the more effectively the graded approach can be applied. In any case, the technical basis for the approach needs to be documented.

2.2.4. Values for bulk and surface contamination

Values for exemption and clearance of material may be expressed as activity concentration values or as surface specific activity values.

The values for surface contamination are generally expressed in Bq/cm^2. Methods for deriving surface contamination values are usually based on appropriate models and scenarios. Examples can be found in Ref. [10] and the supporting Radiation Protection Series 101 [11], in the German Radiation Protection Ordinance [12] or in the ANSI Standard [13]. Such surface specific values need to be distinguished from those provided in the IAEA Transport Regulations [7] for the surfaces of packages and for the surfaces of objects (surface contaminated objects (SCO)) for transport purposes only.

In addition, surface specific values that are derived from activity concentration values simply by assuming a penetration depth and a density of the material are not the same as surface specific clearance levels that are derived from dedicated surface models and scenarios. This approach can be used where there is a clear understanding of the associated assumptions. The surface specific activity calculated from Eq. (2) is simply a projection of activity concentration of a given depth onto the surface. It bears no link to radiological consequences from surface contamination and constitutes no relation to the 10 μSv in a year criterion relevant for clearance.

An activity contamination value can be converted to a surface specific activity value according to the following formula:

$$A_s = A_m \cdot d \cdot \rho \tag{2}$$

where A_s is surface specific activity in Bq/cm², A_m is activity concentration in Bq/g, d is penetration depth of the contamination in cm, and ρ is the density of the material in g/cm³.

Contaminated material, which is to be released from regulatory control, needs to be decontaminated to the appropriate surface specific activity value before the item is monitored for clearance. Although an item is decontaminated prior to direct monitoring, smear samples for removable contamination need to be taken to verify compliance with any limit values for removable contamination. These might also be an issue with volumetric activity if the material is porous or was exposed to a neutron field. In these cases, the activity concentrations will also apply.

2.2.5. Averaging

When specifying radionuclide concentration values, it is not sufficient to specify only activity concentrations in terms of Bq/g or Bq/cm². Averaging masses, volumes or areas of material to be monitored for clearance also need to be specified, along with acceptable confidence levels for false negatives, recognizing that intentional dilution with clean material to reach the activity concentration values for release of material from regulatory control is not an acceptable practice [2]. This subsection focuses on averaging, while uncertainties in the measurements are dealt with in Section 5.

The regulatory body may allow greater averaging masses or areas [14, 15], particularly under the following conditions:

- The material is homogeneously contaminated, e.g. the maximum concentration level of the target material is less than ten times the clearance level;
- The material is properly segregated based on the origin, nature of contamination, type of material, e.g. fragments from dismantled large equipment;
- The concentration values of material are well below the clearance levels.

Different approaches and experiences exist regarding the averaging of masses, volumes and areas of material considered for exemption or clearance. When determining acceptable averaging masses, volumes or areas, care needs to be taken to ensure consistency with any assumptions made in the derivation of the radionuclide concentration limits. For example, Ref. [2] is meant to apply to bulk quantities of material, i.e. quantities greater than about 1 t, and further assumptions are presented in detail in Ref. [9].

The use of averaging quantities in measurements can be interpreted as follows:

(a) In cases where an *averaging mass* is specified, the measurement(s) can take into account the activity from a mass of material less than or equal to this specified mass and divide this activity by the mass which has been measured to obtain activity concentration values. Normally, it is presented as Bq/g or kBq/kg. Larger bulk monitors are capable of measuring material quantities up to 1 t by total gamma measurements (see Section 3.5), so that the activity value obtained in such measurements can be directly related to the net mass in the measurement chamber. The European Commission recommends that the mass over which averaging is allowed generally does not exceed 1 Mg to release building rubble [14]. If the instrument can measure only quantities smaller than the averaging mass, several measurements may be combined until the averaging mass is reached, as long as no single measurement exceeds ten times the activity concentration value [13].

(b) In cases where an *averaging volume* is specified, the procedure is quite similar to the case of averaging masses described above. Regarding the averaging of volumes, for quantities less than about 3 t/a, Ref. [16] suggests that an averaging volume on the order of 0.2–1 m^3 is reasonable. The same range for averaging volumes is suggested by the European Commission in Ref. [14]. It is suggested, as with the mass averaging, that multiple volumetric measurements can be averaged over a volume of 1 m^3 as long as no single measurement exceeds ten times the screening level [13]. Averaging methods for material of low specific activity for transport are provided in Ref. [17]. In the derivation of values for Ref. [2], volumes on the order of 5–10 m^3 or more were used in the potential exposure scenarios. For bulk quantities, an averaging volume of 1 m^3 could be considered a minimum, and perhaps even larger volumes (e.g. up to 10 m^3) may be acceptable, as described later in this section.

(c) In cases where an *averaging area* is specified, which is of a similar size as the surface area measured by the instrument (e.g. averaging area of several 100 cm^2 for surface detectors or 1 m^2 up to several square metres for in situ gamma spectrometers with collimators, see Section 3.5), the activity determined by the instrument can be directly divided by the measurement area to obtain the surface specific activity concentration. If the averaging area is much larger than the instrument surface area (e.g. averaging area of 1 m^2 and measurements performed by a surface monitor with 200 cm^2), several measurements may be combined until the averaging area is reached. In addition, statistical methods may be applied for measuring surface specific activities relating to the averaging area, thus avoiding 100% surface measurements.

Averaging areas for surface monitoring are typically in the range of 100 cm^2 to 1 m^2. The European Commission recommends that the surface area over which averaging is allowed, in general, does not exceed 1 m^2 for clearance of buildings for demolition [18]. The American National Standards Institute and the Health Physics Society [13] suggest that multiple surface activity measurements can be averaged over a 1 m^2 area, with no single measurement exceeding ten times the screening level.

For the case of clearance of bulk quantities of material, using an averaging area of 1000 cm^2 up to 1 m^2 and an averaging mass of several hundred kilograms would be considered reasonable. This would be in accordance with the assumptions made in the scenarios used for the derivation of the values in Ref. [2] as described in Ref. [9].

2.2.6. ‘Hot spot’ values

One of the most challenging tasks in the release of material from regulatory control is to ensure that most or all of the activity is not located in a very small part of the material (i.e. ‘hot spots’). In order to achieve this goal, the regulatory body will need to approve or specify additional monitoring criteria to the averaging criteria mentioned to detect any hot spots in the material considered for clearance. For example, Ref. [16] suggests that each one tenth of the area or volume may not exceed ten times the limit applied to the average.

In many cases, demonstrating compliance with hot spot criteria, as described above, may not require any additional measurements, such as scanning for surface contamination. As long as the averaging area is at least ten times greater than the detector area (which will most likely be true for an averaging area of 1 m^2), the detector will register no more than one tenth of the averaging area at any time. To meet the clearance levels, the monitoring technique will need to be sensitive enough to detect homogeneous surface contamination (spread evenly over the surface). In this case, it will also have the possibility to detect contamination ten times the values over the area of the instrument.

For bulk material, one approach to demonstrating compliance with the hot spot criteria is to use monitoring techniques sensitive enough to detect 100% of the contamination in the ‘worst case’ 10% of the volume. For example, if measurements are taken on the outside of a drum, calculations to demonstrate compliance could assume that all of the contamination is located in the centre of the drum (surrounded by clean material), furthest from the detectors and shielded by the clean contents. This will result in more expensive methods (e.g. longer counting times, more measurements or more sensitive detectors), but the additional cost may be small compared to using an additional sampling measurement to demonstrate compliance with the average and the hot spot criteria.

2.3. HISTORY

Collection of detailed information on the history of material to be exempted or cleared is a very important and sometimes difficult step, in particular for historical sites. It can provide useful information about the expected level of contamination, mixture of radionuclides (short lived and long lived radionuclides) and the nature of contamination (surface or bulk contamination, activation products, etc.) that could facilitate the selection of appropriate monitoring techniques and strategy.

Information can be obtained from various sources such as:

- Historical records (e.g. design of facility or system, log books, routine radiation monitoring records, incident records);
- Knowledge of the types of processes involving the material (e.g. cooling system of the primary loop of a nuclear reactor);
- Experience gained elsewhere (e.g. similar facilities in the country or abroad);
- Public or institutional memory (e.g. workers’ recollections).

This detailed history will need to include information on:

- Knowledge or theoretical estimates about processes or activities during the practice in order to predict contamination conditions, and the physical and chemical form of the contaminants;
- Whether the radioactive contaminants have been enclosed within the restricted areas;
- Whether the material has been potentially activated by neutron exposure;
- Whether the material has been contaminated as a consequence of an accident (the radionuclide spectrum may then be somewhat different from the radionuclide spectrum due to normal operations);
- Whether the building or equipment has been refurbished or modified;
- Whether the material has been decontaminated.

2.4. DETERMINATION OF MATERIAL AND CONTAMINANT CHARACTERISTICS

In order to predict the potential types and levels of contamination, and to select the optimum monitoring strategy for exemption or clearance, it is necessary to define the characteristics of the material. The following information is needed to properly characterize the material:

(a) **Origin.** Type of facility and location within the facility (e.g. nuclear reactor primary system, nuclear fuel fabrication plant, radioisotope production facility hot cells), and if generated during operation or dismantling.
(b) **Type of material.** Physical form of the material (e.g. concrete, stainless steel, plastic).
(c) **Quantity of material.** Estimate of the amount of material in terms of volume, mass or area, either total or, for an ongoing operation, per year.
(d) **Radionuclides.** Specification of the radionuclides present, in particular single radionuclides or mixtures of radionuclides (radionuclide spectra chemical composition); types of emissions (α, β, γ); identification of contamination with specific radionuclides.
(e) **Type of contaminant.** Physical characteristics of the contaminant, only surface contamination (fixed or non-fixed); bulk contamination, activation or a combination of these.
(f) **Homogeneity of contamination.** Identification of hot spots on the surface or within the volume.

(g) **Time frames.** From the occurrence of contamination to the time of measurement are particularly relevant for short lived radionuclides and radionuclides in decay chains.

2.5. MANAGEMENT APPROACH

In order to plan and conduct monitoring for compliance with levels for exemption and clearance, clear allocation of responsibilities (e.g. of operators or other companies/contractors) and adequate resources are required. An organizational structure needs to be established to fulfil the planned monitoring in a timely and effective manner.

Management issues to be considered in monitoring activities include:

- Definition of available and required resources: financial and human resources, monitoring instruments and organizational structure of the project, reuse value of the material.
- Establishment of the appropriate quality management programme (see Section 6).
- Establishment of the personnel requirements, taking into account the necessary expertise and the required level of training or the necessary contribution of contractors.
- Definition and communication with the involved interested parties (see Section 2.7).

More specifically, the management needs to ensure that the following activities are performed in order to assist the decision making process on compliance with release levels:

- Classification and specification of boundaries of the survey units.
- Definition of the null hypothesis, i.e. the residual activity in the survey unit exceeds the release levels.
- Specification of the approach to deal with mixtures of radionuclides and how to establish correlation factors (fingerprint).
- Specification of the approaches for dealing with uncertainties where the consequences of decision errors are relatively minor.
- Definition of Type I decision error (believing that contamination is present when it is absent) and Type II decision error (believing that contamination is absent when it is present), and assigning probability limits for the occurrence of these errors. The probability of making a Type I decision error (α) or a Type II decision error (β) are material specific variables.

- Estimation of the standard deviation (σ) of the measurements in the survey unit.
- Specification of the relative shift (Δ/σ) (Δ is equal to the width of the uncertainty region) generally designed to have a value between 1 and 3, which is used to estimate the number of samples required over a given survey (or averaging) unit.
- Specification of detection limit for all measurement techniques (e.g. scanning, direct measurement and sample analysis).
- Calculation of the estimated number of measurements and specification of measurement locations required to demonstrate compliance. The number of measurements depends on the relative shift, Type I and Type II decision error rates, the potential for small areas of elevated activity, and the selection and classification of survey units.
- Specification of the documentation requirements for the survey, including survey planning documentation; documentation supporting the decision whether or not the material meets the release levels.
- Controls on the material between the time of monitoring and its release to avoid re-contamination or inadvertent release.

2.6. DECIDING ON THE OPTIMUM STRATEGY

An optimum strategy for monitoring for compliance with established levels for exemption and clearance needs to be developed, such that the monitoring efforts are commensurate with the expected contamination of the material and associated hazards. The optimum monitoring is based on the following:

- Optimization of protection measures, taking into account factors such as safety, social factors, etc;
- Minimization of monitoring costs by selecting the most appropriate methods;
- Minimization of on-site handling and off-site transport activities.

Monitoring needs to focus on the fraction of the material likely to be contaminated. Thus, the general approach to monitoring will require all of the material, which can be monitored directly, to be surveyed, unless handling or cost considerations show that it is not the optimal strategy. However, the cost of the optimum strategy can exceed the financial resources of the operator. Revision of the monitoring strategy will need to be considered in that case, for example, adequate monitoring and release of only a part of the material agreed to by the regulatory body, with the remaining material being disposed as radioactive waste.

Material contaminated at levels near the established levels will usually need to be fully monitored. Monitoring of material, which will very likely exceed established levels, needs specific attention and the results are used to further define the future management of material that is not cleared. Material that is probably not contaminated or is contaminated at levels that are unlikely to exceed the exemption or clearance levels, could be subjected to a simplified monitoring scheme, with supporting evidence that there are no hot spots. Use of statistically based methods that consider carefully defined parameters regarding the homogeneity of the contamination, instrument measurement characteristics and monitoring techniques, and activity concentration can significantly reduce monitoring costs. The approach needs to be fully documented and approved by the regulatory body prior to its application.

2.7. INVOLVEMENT OF INTERESTED PARTIES

The number of interested parties involved in the exemption or clearance of material is generally greater than that of the operation of facilities because the material can be used as conventional reusable material or disposed as conventional waste. In order to apply the concepts of exemption and clearance effectively and smoothly, it is necessary to identify the related interested parties to be consulted in establishing the monitoring strategy, its implementation and communication of results. For example, when the operators recommend their own derived values, the agreement of the regulatory body is essential. In that case, the implication of selected values also needs to be explained to the relevant interested parties.

The same process for involvement of interested parties is needed when the operator decides on the monitoring strategy. It is important to establish open and transparent dialogues between the operators and the potential user of the released material (e.g. scrap dealers). For example, in Spain, an agreement was reached between Empresa Nacional de Residuos Radiactivos and the local scrap dealers to receive cleared metal materials from the cleanup of an area within the Centre for Energy-Related, Environmental and Technological Research (CIEMAT) site. When monitoring for compliance with exemption and clearance levels, sufficient and adequate information needs to be provided to the interested parties and also to use transparent procedures on decision making for the monitoring strategy. In terms of communication of the monitoring strategy, during normal operation of a facility, monitoring results will generally be presented and used by experts from the operator or regulatory body familiar with the facility and monitoring process. Any organization receiving material for reuse or disposal will also require results in radiological units, such as Bq/g or Bq/cm^2. It is, therefore, important to ensure that there are measures in place to communicate the monitoring strategy and results to the various interested parties and gain their confidence in compliance with established levels. This will allow better understanding of the accuracy and significance of the reported monitoring results, or corresponding equivalent activities. Any future user of the material is unlikely to have detailed knowledge of the facility releasing the material and may not be familiar with the monitoring equipment and techniques employed.

3. SELECTION OF MONITORING TECHNIQUES AND INSTRUMENTS

3.1. MONITORING STRATEGIES AND TECHNIQUES

Monitoring for compliance with exemption or clearance covers the measurement of activity for reasons related to the assessment or control of potential exposure to radiation or radioactive substances, and the interpretation of the results.

In this relation, a *monitoring strategy* can be described as a material flow process, with the material to be monitored as inputs, the monitoring techniques and material handling processes as part of the flow, and the final material disposition as outputs (Fig. 2). The inputs are various types of material to be monitored, possibly subdivided into ‘expected’ or ‘potentially’ contamination categories (e.g. ‘expected clean’ or ‘potentially contaminated’), or types of contamination (e.g. surface versus bulk; alpha emitters versus gamma emitters). The outputs of this flow are the clearance of material, further processing or disposal within a regulated facility.

A *monitoring technique* is a tool used in the monitoring strategy to facilitate the decision on compliance with established levels. It combines the selection of an instrument with a protocol describing how it is to be used in both direct and indirect monitoring. For direct methods, the instrument is used to directly measure the material being monitored, and for indirect methods, contamination is transferred to secondary media or a sample is taken (swipes, etc.), and this sample or media is monitored.

The link between a monitoring strategy and techniques can be illustrated with the following example (Fig. 2) — bulk contaminated concrete and surface contaminated metal (e.g. steel) need to be monitored with two possible final management options: clearance or disposal as radioactive waste.

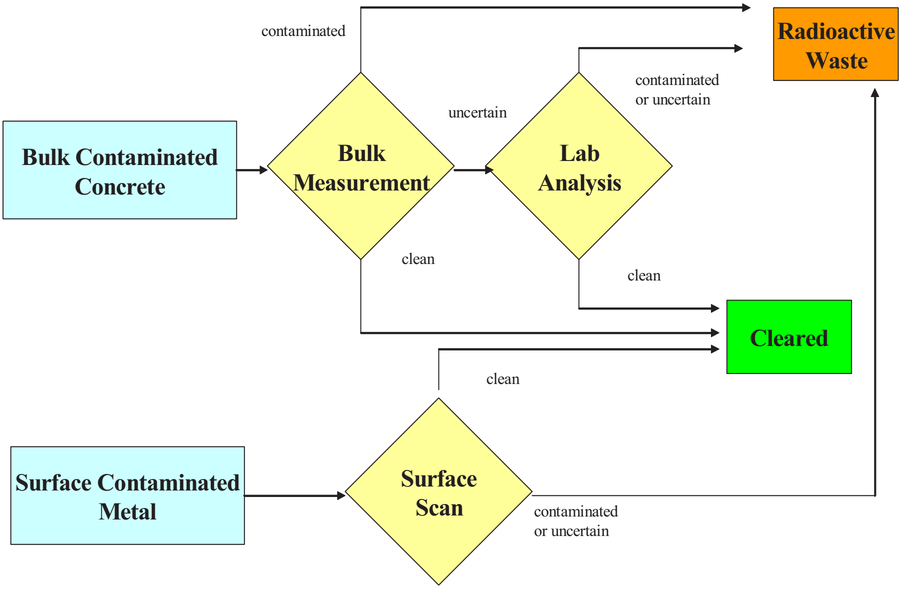

FIG. 2. A general monitoring strategy presented as a material flow process.

Three monitoring techniques have been selected for the purpose of monitoring: surface scan, bulk measurement and sample collection with subsequent laboratory analysis. Surface scan and bulk measurement are relatively inexpensive and involve reasonably precise methods in cases where the radionuclide composition is known and the radionuclides are readily measurable. Laboratory analysis is more precise and expensive, and can be used to determine the radionuclide composition. Materials subjected to each of these monitoring techniques are classified as 'contaminated' (i.e. clearly above clearance levels), 'clean' (i.e. clearly below clearance levels) or 'uncertain' (i.e. possibly above or below the clearance levels). In the final analysis, the material falling into the categories of contaminated and uncertain material is intended for decontamination or disposal as radioactive waste, and the material that can be shown to be clean can be released from regulatory control.

The example illustrated in Fig. 2 can be used to demonstrate a general principle: sometimes it is beneficial to use a monitoring technique that is not fully capable of defining exactly whether material is above or below clearance levels. It is often the case that the material can be efficiently scanned to determine which fractions are clearly above or below the levels, leaving only a relatively small fraction of uncertain material. More expensive 'secondary' monitoring techniques can then be reserved and used for monitoring of this relatively small fraction.

3.2. USE OF MULTIPLE MONITORING TECHNIQUES IN SERIES

Depending on the material to be considered for release from regulatory control, some monitoring strategies can consider utilization of one or more monitoring techniques. If the task is to monitor 1000 m^3 of 'bulk contaminated concrete', Table 1 shows the average cost per m^3 (for illustrative purposes only). The two monitoring techniques and, for a given batch of material, the fraction of the material that each technique can clearly show either meets or exceeds the levels. In Table 2, three monitoring strategies are considered:

- Strategy A that uses measurement of bulk material only;
- Strategy B that uses sampling and subsequent laboratory analysis only;
- Strategy C, where all of the material undergoes measurement of bulk material;
- The uncertain fraction then undergoes laboratory analysis, as shown in Fig. 2.

TABLE 1. EXAMPLE OF COST AND PRECISION OF TWO MONITORING TECHNIQUES

Monitoring technique	Measurement costs ($/m)	Fraction of material that meets clearance levels (%)	Fraction of material that exceeds clearance levels (%)	Fraction of material that is uncertain (%)
Measurement of bulk material	100	70	5	25
Sampling/laboratory analysis	300	85	10	5

TABLE 2. EXAMPLE OF COMPARISON OF TOTAL COSTS

Strategies	Monitoring costs ($)	Disposal costs ($)	Total cost ($)
A: Measurement of bulk material only	100 000	300 000	400 000
B: Sampling/laboratory analysis only	300 000	150 000	450 000
C: Both techniques in series	175 000	150 000	325 000

In each case, disposal costs of of US \$1000/m^3 are applied to all material for which it cannot be demonstrated that it meets the clearance levels. Table 1 compares the total cost of using each of the three monitoring strategies.

In this case, the most cost effective monitoring strategy (i.e. the one with the lowest total cost) is Strategy C, the option that uses both monitoring techniques in series. Further discussion on using multiple monitoring techniques and waste segregation can be found in the following section and in Ref. [19].

3.3. PHYSICAL SORTING TECHNIQUES

In some cases, it can be useful to employ physical sorting techniques, as opposed to sorting techniques that rely on radiological (or other) measurements. If the material in question is contaminated by discrete objects of a specific size, other physical or chemical material characteristics, a physical sorting technique based, for example, on the size of the objects could be used to:

- Remove the discrete objects;
- Improve homogeneity of different groups of material subject to monitoring;
- Facilitate the averaging process;
- Facilitate analysis of monitoring results and decision on compliance with established levels.

However, implementation of monitoring techniques for the individual batches (groups of material) after sorting would still be necessary to demonstrate compliance of each material group with established clearance levels.

In order to facilitate monitoring of material considered for exemption or clearance, it could also be beneficial to divide the facility during operation into specific areas/categories according to the radiological risk (also called ‘zoning’). The monitoring strategy applied afterwards can then take into account the characteristics of the specific areas of the facility and of the particular material originating from this area.

3.4. DEALING WITH MIXTURES OF RADIONUCLIDES

For some facilities using radioactive material, a mixture of radionuclides in known ratios (also called correlation factors) could have been determined during the operational phase of the facility if the radionuclides used and their relative ratios did not change significantly over the lifetime of the facility. One important use of the correlation factors is that it can allow the estimation of activity concentrations of radionuclides that cannot be easily monitored. These include low energy beta emitters, which do not include either energetic beta radiation or photon radiation from their decay chains (i.e. ^{3}H, ^{63}Ni and ^{14}C). Monitoring of such radionuclides normally requires liquid scintillation counting or expensive, slow radiochemistry. If, on a limited but thorough series of measurements, these difficult radionuclides are found to be roughly in fixed proportion with other easier to measure radionuclides (called 'key radionuclides'), such as $^{137}Cs + ^{137m}Ba$ or $^{90}Sr + ^{90}Y$, then a case can be made that a stable radionuclide composition exists and specific measurements of the difficult radionuclides might not be required. A case in point is the use of ^{60}Co to monitor a wide range of difficult to measure radionuclides associated with activation products and corrosion products associated with the operation of reactors.

In some facilities, one set of correlation factors can apply over a large area or, in some cases, only one radioactive material may have been used. Allowing the decay of the short half-life radionuclides for a period of time, for example, ten years, could leave a simpler mix of longer half-life radionuclides. Alternatively, waiting for decay of shorter half-life radionuclides may affect the ability to measure potential key radionuclides, such as ^{60}Co with its 5.24 a half-life. The radionuclide composition may vary considerably over time in a certain facility, particularly where chemical processes have taken place. Radionuclide composition will also vary where the activity generated by neutron activation and the concentration of impurities in the material play a significant role. Quite small variations in the cobalt content of steel, for example, can have a large influence on the resulting activation products and also on the resulting contamination by rust. Another example is the neutron activation of concrete impurities resulting in trace amounts of europium in the concrete.

In practice, all radiation monitoring equipment has a response which depends on radiation type, energy and geometry. The response of the equipment that will be used will have to be calculated for the mix of radionuclides expected to be measured. When the radionuclide mixture is used during the release of material during the decommissioning of nuclear power plants, it is necessary to select one or more key radionuclide(s) as well as the other radionuclides to be evaluated for compliance with clearance. An example for the selection method proposed in Japan consists of two steps [20] (Fig. 3):

(a) In the first step, a key radionuclide is selected that gives relatively high values of C/CL among the radionuclides considered and is easily measurable. Then a measure of significance is introduced which is a relative ratio defined by $(Cj/CLj)/(C/CL)_{key}$, where $(C/CL)_{key}$ means the ratio for the key radionuclide, and significant radionuclides are selected as they satisfy the inequality $(Cj/CLj)/(C/CL)_{key} > 0.01$.

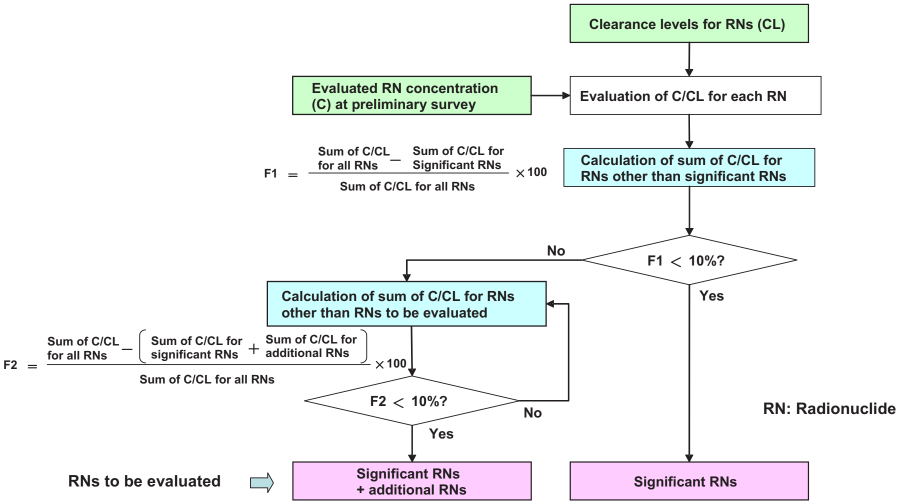

FIG. 3. An approach to selection of key radionuclides to be evaluated.

(b) In the second step, the sum of C/CL for all radionuclides considered and the sum of C/CL for significant radionuclides are calculated. Then, if the difference between the two sum values, F1, is less than 10%, the significant radionuclides are recognized as ones to be evaluated. However, if not, the sum of C/CL for the significant radionuclides and an additional one are calculated. If the difference, F2, is less than 10%, the additional radionuclide is included in radionuclides to be evaluated. If not, the same procedure is repeated until radionuclides to be evaluated have been selected.

The response of each monitoring system can then be calculated in terms of the radionuclide composition. This approach can also allow a calculation of the likely variation in response of contamination monitoring equipment with the surface contamination. If the equipment, for example, has a good response over a wide range of beta energies, then the response will change quite quickly with the degree of self-absorption. Sometimes, a safety factor needs to be introduced, particularly if a significant proportion of the emissions are of low energy.

It may be necessary to consider whether the radionuclide composition (and the correlation factors) needs to be re-evaluated as monitoring of material proceeds, particularly on old, complicated facilities that are found not to be well characterized. Quite simple means can sometimes be employed to check on radionuclide composition stability, such as the ratio of the count rates from two different types of monitors or the influence of an absorber placed between the contaminated surface and the monitor. Gamma spectrometry is also a relatively cheap and easy process that can be employed to check on the photon emitting component. A combination of gamma spectrometry and gross beta measurement can also demonstrate stability where the main contaminants are ^{137}Cs + d, a gamma and medium energy beta emitter, and ^{90}Sr + ^{90}Y, a medium and a high energy beta emitter (see Section 5).

In the following example, the matrix has a mixture of two radionuclides consisting of 75% ^{14}C (clearance level = 1 Bq/g) and 25% ^{238}Pu (clearance level = 0.1 Bq/g). The effective clearance level based on Ref. [2] is the following:

$$\frac{1}{CV_{\text{eff}}} = \frac{0.75}{1\ \text{Bq/g}} + \frac{0.25}{0.1\ \text{Bq/g}} \tag{3}$$

$$CV_{\text{eff}} = 0.31\ \text{Bq/g}.$$

This is only true when the ratio of the radionuclides is 75% ^{14}C and 25% ^{238}Pu.

3.5. INSTRUMENTATION SELECTION

3.5.1. Types of instruments

There is a broad range of instruments that can be considered for use in monitoring of material for compliance with established levels for exemption or clearance, including ionization chambers, proportional counters, Geiger–Müller detectors, scintillation detectors and solid state detectors. Combinations and modifications of these instruments have led to an even larger variety of measurement techniques, such as bulk monitors, where a measurement chamber is surrounded by an array of large area scintillation detectors, or collimated in situ gamma spectrometry, which is suitable for quantitative measurements of gamma emitting radionuclides on surfaces as well as in the volume beneath the surface.

Ionization chambers are not usually used in monitoring for compliance with clearance levels due to their relatively low sensitivity, relatively high cost and size. In addition, most relatively sensitive ionization chambers use pressurized gas-filled chambers that are considered dangerous goods for transport by air.

Proportional counters can be particularly useful for many clearance applications. They can be in two main forms:

(a) Thin window gas flow or refillable detector, which can be used for alpha or alpha and beta radiation monitoring.

(b) The sealed xenon filled counter, which has a thicker window (and is, therefore, insensitive to alpha radiation) but which has a useful response to low energy X rays. In addition, they are not susceptible to magnetic fields and will identify the presence of high beta or gamma fields by showing a high count rate in the beta channel.

Thin window Geiger–Müller detectors are frequently used for beta surface contamination monitoring. They have very low detection efficiency for gamma radiation and X rays, resulting in a relatively low background count rate. They are not used for alpha surface contamination monitoring because of their window thickness and comparatively high background, in this case. The main operational disadvantage is the ease with which they can be damaged.

Scintillation detectors are used for surface contamination monitoring of alpha, beta, low energy gamma and X ray radiation, depending on the type and thickness of scintillation material used. Scintillation detectors are also often used in measurement of bulk gamma radiation contamination. For this application, thicker, larger volume scintillators are used. However, scintillation detectors are susceptible to magnetic fields and might be unreliable in high radiation fields (see Section 3.5.2).

Plastic scintillators are typically used to detect beta and low energy gamma radiation. Thicker plastic scintillators and thallium activated sodium iodide (NaI (Tl)) scintillators are used for the measurement of X ray and gamma radiation. Thinner crystals (approximately 1.8 mm thickness) are used for lower energy (<100 keV) X rays and gamma radiation. A zinc sulphide scintillator deposited on mylar film is used for alpha detection. ZnS does not respond efficiently to beta or gamma, but the light pipe and photo multiplier may respond to high gamma or neutron fields.

Solid state detectors can be very useful in bulk contamination monitoring. They are not normally used in surface contamination monitoring, however, because a number of instruments have been developed for this purpose. In particular, the very good energy resolution of high purity germanium (HPGe) detectors can be beneficial under certain circumstances. Some practical disadvantages exist with the use of HPGe detectors, such as expense, cooling and complicated electronics.

Bulk monitors (also known as bag monitors, box monitors or release measurement facilities) consist of a measuring chamber which can have a volume of several tens of litres up to more than 1 m^3, surrounded by an array of large area scintillation detectors, resulting in a 4π measurement geometry for gamma radiation from the material. Depending on the size of the chamber, a number of 6 to 24 detectors (four per side) surround the items to be measured, which is usually inserted into boxes or drums placed on a tray. Automatic weighing and

FIG. 4. Bulk monitor manufactured by RADOS (now MIRION Technologies) [21].

positioning of the tray reduce operating requirements to a minimum. An example of a bulk monitor is shown in Fig. 4. Such devices are widely used, especially in decommissioning projects where there is a high material throughput for clearance.

Collimated in situ gamma spectrometers typically consist of HPGe solid state detectors surrounded by circular shielding elements which restrict the sensitivity of the instrument to a cone shaped region (Fig. 5). Such instruments allow the measurement of gamma radiation from surfaces and from the volume underneath (the depth depending on the gamma energies of the radionuclides in question and on the material properties, usually between a few centimetres for metal and several tens of centimetres for loose building rubble and high energy gamma emitters). As the collimator restricts the angle through which gamma quanta can enter the detector, the measurement results can be attributed to a certain area or a certain volume allowing quantitative measurements of surface or activity concentration values. By varying the opening angle and/or the distance of the instrument from the surface, the area and/or the volume from which gamma quanta are registered can be measured. Such instruments are widely used where large areas, such as building surfaces, have to be cleared. The collimator and distances are usually set in such a way that the area seen by the instrument is in the range of 1 m^2 or a few square metres.

FIG. 5. In situ gamma spectrometer with a collimator manufactured by CANBERRA [22].

3.5.2. Instrument selection

Before selecting an instrument, it is important to understand both the activity concentration values that are to be verified, the capabilities of the monitoring instruments and the characteristics of the potentially contaminated material. Some types of instruments are quite expensive, and may limit their availability. In such cases, the analysis of instrumentation type is considered against production rates. It may be quicker to employ a more expensive type of monitoring instrument, but if a greater number of cheaper instruments can be obtained, the monitoring process may be optimized with cheaper instruments. In addition, if time is not so critical, use of a slower, cheaper method of monitoring may be acceptable or even preferred.

Answers to the following questions about the potentially contaminated material or objects will assist greatly in selecting the most appropriate instrument and monitoring technique:

(a) What is/are the radionuclide(s) of concern?
(b) Do they emit alpha, beta or gamma/X ray radiation?
(c) At what energy are the emissions?
(d) Is the material contaminated throughout or is the contamination deposited on the surface?
(e) If the contamination is on the surface:
    (i) Is it a smooth, impermeable surface (relevant for the depth distribution of the contamination)?
    (ii) Is it a flat surface (relevant for monitoring beta and alpha emitting radionuclides)?
    (iii) Has the contaminated surface been painted over (relevant for beta and alpha emitting radionuclides, not for measurements of gamma activities)?
    (iv) Does the surface appear (visually) clean (relevant for measurements of alpha and low energy beta emitting radionuclides)?
(f) Could the fingerprint method (i.e. using correlation factors) be used?
(g) What are the key radionuclides?

Having answered these questions, Table 3 could be consulted for general recommendations for selecting monitoring instrumentation. Appendix I also includes information that can help to determine appropriate monitoring methods for specific radionuclides.

TABLE 3. GENERAL APPROACHES USED TO MONITOR FOR COMPLIANCE WITH CLEARANCE LEVELS FOR VARIOUS SURFACES OR BULK CONTAMINATION, AND VARIOUS TYPES OF RADIOACTIVE EMISSIONS

Type of contaminated surfaces / Types of contamination	Surface		Bulk material
	Smooth, impervious, clean surface	Rough, porous, dirty or painted surface	Bulk contamination
Alpha radiation	Direct measurement is possible using, for example, alpha sensitive scintillation detectors or proportional counters. Swipes or swabs can also be used for indirect measurement of loose contamination if necessary. Long range alpha detection techniques might be useful.	Direct measurement is not possible, although it should be considered whether the contaminant also emits low energy X rays. Depending on the surface, it could be possible to use swipes or swabs for indirect measurement of loose contamination if necessary.	Direct measurement is very difficult or impossible. Radiochemical analysis of representative samples is likely to be the appropriate approach.
Beta radiation	Direct measurement is possible using, for example, scintillation detectors, proportional counters or thin walled or mica end window Geiger–Müller detectors. Swipes or swabs can also be used for indirect measurement of loose contamination if necessary.	Direct measurement may be possible using, for example, scintillation detectors, proportional counters or thin walled or mica end window Geiger–Müller detectors. Depending on the surface, it may be possible to use swipes or swabs for indirect measurement of loose contamination if necessary.	Direct measurement may be possible using, for example, large area scintillation detectors or proportional counters filled with a low atomic number gas. Radiochemical analysis of representative samples may prove necessary.
Gamma radiation	Normally, surfaces are monitored for alpha or beta radiation. Large surfaces can be monitored with in situ gamma spectrometers with collimator.	Normally, surfaces are monitored for alpha or beta radiation. Large surfaces can be monitored with in situ gamma spectrometers with collimator.	Direct measurement likely possible using scintillation or solid state detectors, bulk monitors etc; also in situ gamma spectrometers with collimator can be used if volumes are not too thick.
Low energy gamma radiation or X rays	Direct measurement is possible using, for example, sodium iodide scintillation detectors, or sealed, xenon filled, titanium windowed proportional counters. Swipes or swabs may also be used for indirect measurement of loose contamination if necessary.	Direct measurement is possible using, for example, sodium iodide scintillation detectors, or sealed, xenon filled, titanium windowed proportional counters. Depending on the surface, it may be possible to use swipes or swabs for indirect measurement of loose contamination if necessary.	Direct measurement may be possible using scintillation or solid state detectors, but thin samples are necessary unless it can be demonstrated that contamination is uniform throughout the matrix.

Having determined the general type or range of instruments appropriate to the task, additional considerations are required to select the specific instrument and technique. The selection of specific instruments needs to include the following considerations, at a minimum:

- The instrument is sufficiently sensitive to operate at the low level of contamination to be detected and does not require excessive integration time (is it be capable of detecting activity levels approximately one tenth of the clearance level?);
- The instrument response to background radiation is not limiting, which may necessitate identifying an area of lower background to perform the monitoring;
- The energy response is sufficient over the energy range of interest, where applicable (note that use of a fixed radionuclide composition could effectively reduce this energy range);
- The detector is rugged and protected to minimize damage in use;
- The detector is not responsive to magnetic and electromagnetic fields;
- The detector is not sensitive to saturation processes, i.e. at high radiation levels (however, as clearance usually addresses low levels of contamination, this limitation might not be considered as critical);
- The detector is able to discriminate alpha, beta and gamma radiation, where required;
- The calibration and testing procedure is technically based, clearly written and can be easily achieved;
- The instrument can access the necessary areas (e.g. inside a pipe) and can be used at the required distance from the objects or material (e.g. curved surfaces limiting the size of the detector);
- The instrument is easy to handle;
- The instrument is fitted with an audio output or alarm, to alert the operator in case of excess contamination;
- The instrument is easy to maintain;
- The cost of the detectors is commensurate with the overall financial aspects of the clearance activities.

More detailed information on the properties of specific types of instruments is presented in Table 12 in Appendix III and other references [23, 24]. It is important to note that although Table 12 covers primarily radiation detection instruments, it also includes a few other types of instruments that measure atomic mass or emissions (LA-ICP-AES[8] [25], LA-ICP-MS[9] [26] and chemical speciation laser ablation/mass spectrometer) that can have a use in more challenging clearance projects. In addition, considerations for the direct monitoring of surface contamination are also described in Appendix III.

3.6. DEVELOPMENT OF NEW TECHNIQUES

Technology related to monitoring for clearance of material from regulatory control is changing and improving rapidly. New monitoring equipment and techniques are being developed and applied to monitoring challenges around the world. Before embarking on a major monitoring project, it is worthwhile searching the available literature and consulting other organizations or Member States that have experience and have encountered similar challenges in the past.

For example, a developing technology is stand-off radiation detection based on the ability to detect radiation at a distance, e.g. ultraviolet photons emitted from atoms in the air that have been excited by nearby alpha, beta or gamma radiation sources. Using this technology, alpha sources of a few 10^7 Bq have been imaged at tens of metres with high signal to noise ratios [27], which is, however, not yet sensitive enough for clearance measurements. Although this technology is still in the experimental stage, it may eventually emerge as a useful tool for monitoring large surfaces (such as walls, floors and ceilings) for alpha contamination.

3.7. PHYSICAL CONTROL OF MATERIAL

Material that is to be exempted or cleared is typically put into batches. The batches consist of the same type of material to be released, the same radionuclide mix, same history of deposition of radionuclides or activation, same background, etc. A technical basis document is developed that shows assumptions, choice of instruments and rationale for that specific equipment, process (scan speed, etc.), limitations, etc. Next, based on the technical basis document, a procedure is developed and approved for dispositioning the batch. When the batch is completed, another batch of the same material is then processed. If another batch of that material is not ready, a batch of a different material can be processed. The next batch will require its own technical basis document and procedure.

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[8] Laser ablation inductively coupled plasma atomic emission spectrometry.

[9] Laser ablation inductively coupled plasma mass spectrometry.

Items that are chosen for a given batch are identified in some manner. If the material consists of excess equipment, the equipment serial number can be used for identification. If a soil pile is used, the pile may be identified by its GPS location and date. When the monitoring and sampling is completed, and the analytical results are evaluated and returned, if any material does not meet the clearance level, the specific item can be identified and pulled from the batch.

A batch of material needs to be segregated so that no other material can be added to the batch, or any material removed before it is declared as able to be cleared or not. Once it is declared to be cleared, it is removed from the area to minimize the potential for re-contamination. Normally, material that has been segregated has barriers placed around it. The barriers may consist of yellow and magenta rope with postings, for example. The area that a batch is to be placed in is surveyed prior to the material being placed in there, and then surveyed again after the material is removed.

4. MONITORING CHALLENGES

Challenges during monitoring for compliance could be categorized as technical and managerial (see also Section 6). Most of the challenges addressed in this section are focused on the technical challenges that can be significantly reduced or simplified if measures are taken in the design and the operational phase of the facility to reduce the generation of waste; to select material for the structures, systems and components with low and homogeneous background radiation levels; and to select material that has surfaces that are easy to decontaminate. Appropriate segregation of material of different types and the avoidance of mixing potentially contaminated material with clean material will help the process of monitoring for compliance with established levels. Keeping records of any events which resulted in a spread of contamination on-site and off-site, including information on the details of the areas contaminated, the radionuclides involved and any cleanup measures taken, will also provide data that can be used in the planning process.

4.1. CONVERTING VALUES TO OPERATIONAL UNITS

Once a monitoring technique has been selected, the established values are converted into measurement units applicable to that monitoring technique. For example, an instrument can read in counts per second (counts/s), while the activity concentration value is normally expressed in Bq/g. The technician operating the instrument is required be able to compare the instrument reading with a derived value in the same units. It is not sufficient to simply perform empirical or theoretical calculations to derive the counts/s equivalent to the Bq/cm^2 or Bq/g as account needs to be taken of the measurement uncertainties as discussed in Section 5 of this Safety Report, as well as the background count rate.

For the purposes of illustration, the following two examples are considered. It is noted that these examples are intended to illustrate only one particular aspect of monitoring challenges and are not to be viewed as a comprehensive example. The first example illustrates the case when monitoring for a single radionuclide for comparison to an established value for activity concentration, and the second example illustrates the case when monitoring for a spectrum of radionuclides for comparison to values for surface contamination:

(a) Calculation of a gamma radiation detector count rate

A load of concrete bricks, uniformly contaminated with ^{137}Cs, needs to be monitored prior to clearance. It is decided that the Ref. [2] level of 0.1 Bq/g for ^{137}Cs will be used. It is further decided that the concentration will be averaged over each brick, and that it is sufficient to show that the established level is met with 97.5% probability for each brick.

Each brick will be monitored individually using a 2 × 2 NaI(Tl) detector on contact with the largest side of the brick. This type of detector has a sensitivity of approximately 200 counts/s per Bq/g for ^{137}Cs in a semi-infinite geometry [28]. Factoring in geometry effects to account for the size of the brick (also see Appendix XIII), it is estimated that the response of the detector is 50 counts/s per Bq/g for ^{137}Cs from a single brick (this can be calculated numerically, but in a practical case needs to be derived or verified empirically). For simplicity, it should be assumed that the measurement error is essentially constant in the neighbourhood of 250 counts. Further, the background count rate for this instrument in the well shielded, low background location where the measurements will be taken is 20 counts/s. A count time of 10 s/measurement has been selected to detect the clearance level of 0.1 Bq/g. This level is expected to result in 250 ± 32 counts.

During the 10 s integrated count, the background is 200 ± 28 counts at 2σ plus 50 ± 14 counts at 2σ due to contamination in the brick. The gross count is 200 counts + 50 counts and the propagated error is: $\mathrm{Err} = (28^2 + 14^2)^{½}$ or 32 counts.

Therefore, to be 97.5% confident that an individual brick does not exceed the values, the total number of counts in the integrating period must not exceed

218 (250 – 32). Thus, 218 counts in the 10 s counting interval is the derived limit to be used as part of the monitoring technique described above. It should be noted that if the measurement error is treated more carefully, discussion of which is beyond the scope of this Safety Report, the derived limit becomes 220 counts.

In this example, one could expect a relatively large number of false positives, given that the derived limit is well into the range of the background count (i.e. for a brick containing no ^{137}Cs) of 200 ± 28 (2σ). In this case, one could expect a false positive rate of 10%, i.e. the derived limit will be exceeded for one in ten 'clean' bricks. Possibilities for reducing the false positive rate include: reducing the background count rate (through shielding or simply selecting an area of lower natural radioactivity); increasing the integrating time; or increasing the sensitivity of the detector. However, reducing the false positive rate may or may not be desired, depending on the cost of not clearing 10% of material (increased disposal costs) compared to the cost of decreasing the false positive rate (increased monitoring costs).

(b) Calculation of a beta instrument response for a radionuclide spectrum

In most circumstances, contamination will cover a range of radionuclides, generating different types and energies of radiation. Sometimes the dominant radionuclides can be available as calibration sources, such as ^{90}Sr + ^{90}Y, but often some will not. In the latter case, two steps must be followed:

(i) To estimate the response to each radionuclide, based on available measured response data;
(ii) To combine these results into a reference response for the radionuclide composition.

In cases where several radionuclides are present, the response of a surface contamination monitor is determined by the properties of all of the radionuclides present. The calculation of the combined response function needs to take into account the response functions for the single radionuclides which are either supplied by the manufacturer of the instrument or are determined from measurements of calibration samples of the respective isotopes. The following example illustrates the procedure. It is assumed that a mixture of the radionuclides, ^{60}Co, ^{90}Sr (with ^{90}Y) and ^{63}Ni, is present on a metallic surface. The correlation factor, i.e. the percentages of these radionuclides, is assumed to be 50%, 15% and 35%, respectively. The response function η for an arbitrary instrument is given in Fig. 6 for the pure radionuclides as a function of distance between instrument window and sample. It can be seen that the efficiency

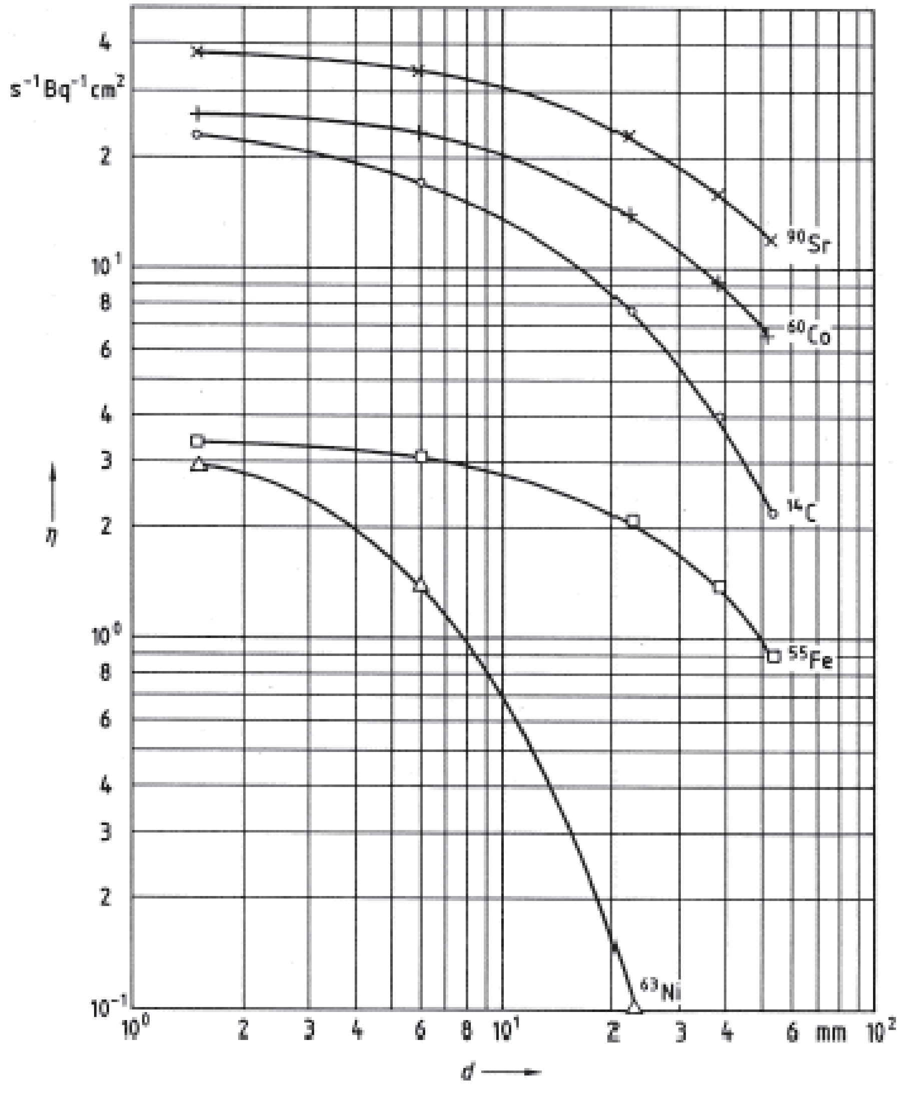

FIG. 6. Efficiency η of a surface contamination monitor (detector area of 9.4 × 16.6 cm², calibration sample 8 × 12.5 cm², P-10 gas filling Ar/CH_4 and window thickness 0.3 mg/cm²) for various radionuclides as a function of distance D between instrument and calibration sample.

decreases with distance, but that the decrease is less steep for radionuclides that emit beta particles of higher energy (^{90}Sr, ^{60}Co) than for those with beta particles of lower energy (^{63}Ni). In the example referred to above, the calibration needs to be calculated for a distance of 10 mm between the instrument window and the surface of the parts to be measured, which could have been determined as the standard operating procedure for scanning surfaces in that particular case. The following values of η are taken from Fig. 6:

$\eta(^{60}\mathrm{Co}, 10\ \mathrm{mm}) = 20\ \mathrm{s}^{-1}\cdot\mathrm{Bq}^{-1}\cdot\mathrm{cm}^2$;
$\eta(^{90}\mathrm{Sr}, 10\ \mathrm{mm}) = 30\ \mathrm{s}^{-1}\cdot\mathrm{Bq}^{-1}\cdot\mathrm{cm}^2$;
$\eta(^{63}\mathrm{Ni}, 10\ \mathrm{mm}) = 0.7\ \mathrm{s}^{-1}\cdot\mathrm{Bq}^{-1}\cdot\mathrm{cm}^2$.

The combined response function for the radionuclide vector given above would then be:

$$\begin{aligned}\eta(10\ \mathrm{mm}) &= (0.5\cdot 20 + 0.15\cdot 30 + 0.35\cdot 0.7)\mathrm{s}^{-1}\,\mathrm{Bq}^{-1}\ \mathrm{cm}^2\\ &= 14.7\ \mathrm{s}^{-1}\mathrm{Bq}^{-1}\mathrm{cm}^2\end{aligned} \tag{4}$$

indicating that 14.7 counts/s can be expected if 1 Bq/cm² total activity of the radionuclide composition specified above were present.

If other radiation, such as alpha or low energy X ray radiations are present, then the detector responses to these can also be combined with that for beta radiation to give an overall response to the radionuclide spectrum (see Section 3.4 for a method to estimate the clearance level in Bq/g for a mixture of radionuclides).

4.2. DEALING WITH UNCERTAINTIES

There are many sources of uncertainty inherent to the monitoring of material for clearance, including:

(a) *Vagueness* regarding the characteristics of the material, including imprecise estimates of material volumes or masses, and imprecise knowledge of the contamination values and the mix of radionuclides. Vagueness can be dealt with by regularly reviewing the characteristics of the material encountered as the monitoring proceeds. It is important to have an adequate characterization process of the facility and material at the start of the project, and only move on to further steps when the material is well characterized (see Fig. 1 and Sections 2.4 and 5.1). The further the project progresses, the more information on the characteristics of the material will be available. Monitoring techniques need to be designed so that information on material characteristics can be easily collected 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.

(b) *Measurement uncertainty* associated with monitoring techniques and results, which are discussed in more detail in Section 5.

(c) *Human errors* that are difficult to quantify, such as improper recording, loss of samples, incorrect labelling, errors during sample preparation such as cross-contamination and measurement device contamination [29]. Various aspects of human errors are discussed further in Section 6.

All sources of uncertainty need to be taken into account when selecting monitoring techniques and instruments.

4.3. TREATMENT OF BACKGROUND ACTIVITY

In monitoring for compliance with exemption or clearance levels, it is important to consider the contribution of natural background. Natural background depends on the radionuclide content of the material to be released (natural or artificial) and the area where the survey will take place.

When using the concept of clearance of material from a facility, the background activity prior to the practice in question needs to be taken into account. Natural background, i.e. activity concentrations associated with natural sources, such as ^{40}K and the radionuclides of the ^{238}U and ^{232}Th decay chains or any other sources in the environment which are not amenable to control [30], need not be taken into account or, can be excluded. A particular case where care is necessary could be a fuel fabrication plant where U has been treated and could have caused contamination on building structures. If those building structures are to be cleared, only that part of the U that originates from the plant operation needs to be accounted for while the U (and its decay products) in the original building structure can be disregarded. Similar considerations apply to measurements made with regard to exemption.

When using the concept of exclusion, the measurements usually relate to radionuclides present in nature (see Ref. [2] and Section 3.2). Thus, the following considerations apply only to clearance (or exemption) measurements.

4.3.1. Characteristics of natural background

When determining what background needs to be subtracted during clearance measurements of building material, variations in the natural background activity level need to be considered. Levels can be established in terms of activity concentration levels above background, or in absolute terms. In either case, it is necessary to determine the background level as the baseline for comparison with the established clearance levels.

Background activity levels are specifically important in demonstration of compliance of material contaminated with naturally occurring radionuclides that are present in the environment (such as ^{3}H, ^{14}C, ^{40}K, uranium and thorium and their progeny). The background activity is also important for the clearance of material contaminated with artificial radionuclides that could also be found in the environment due to nuclear weapon test fallout, Chernobyl or other major accident fallout (see Table 4, taken from Table 1 of Ref. [31]). Other references can be found in the literature [8, 32].

In the ideal case, measurements of material that is similar to that which will be derived but has not been exposed to contamination or activation, needs to be used to establish the materials background count rate for the specified instrument and monitoring technique. This is, however, usually not the situation, so other

TABLE 4. TYPICAL AND MAXIMUM ACTIVITY BACKGROUND CONCENTRATIONS IN COMMON BUILDING MATERIAL AND INDUSTRIAL BY-PRODUCTS USED IN BUILDING MATERIAL IN THE EUROPEAN UNION [31]

Material		Typical activity concentration (Bq/kg)			Maximum activity concentration (Bq/kg)		
		Ra-226	Th-232	K-40	Ra-226	Th-232	K-40
Common building material	Concrete	40	30	400	240	190	1600
	Aerated and lightweight concrete	60	40	430	2600	190	1600
	Clay (red) bricks	50	50	670	200	200	2000
	Sand-line bricks	10	10	330	25	30	700
	Natural building stones	60	60	640	500	310	4000
	Natural gypsum	10	10	80	70	100	200
Common industrial by-products used in building material	By-product gypsum (phosphogypsum)	390	20	60	1100	160	300
	Blast furnace slag	270	70	240	2100	340	1000
	Coal fly ash	180	100	650	1100	300	1500

measurements will generally be required. Therefore, background values are usually estimated by measurements of the same type of material and objects in locations where it can be ensured that they have not been contaminated by any activity involving radioactive substances or activated. This implies that the appropriate material and objects are often collected at a significant distance from the facility. For some material (e.g. concrete), contamination caused by nuclear weapon tests and Chernobyl fallout, distribution of radionuclides from these sources will be non-uniform. The background chosen for use in the exemption and/or clearance process needs to be technically based and documented, then approved by the regulatory body.

For many materials or objects which can contain significant concentrations of natural radionuclides (e.g. bricks), it can be difficult to select reference materials and objects comparable to those to be cleared. The natural variability of the natural radionuclide content of such materials or objects is often large and the assessment of the background values can require a number of measurements in order to obtain consistent statistical distributions. The variation in background activity levels has important implications. Brick is normally more active than concrete, provided the concrete is not made from granite chips. This can result in quite different count rates measured in one part of a building compared to another. For example, in a building made from low activity concrete, the typical count rate on a 50 mm × 50 mm sodium iodide detector is 50 counts/s, whereas in a brick building it can easily reach 200 counts/s. This value can be exceeded where some types of tiles are used or where the building materials include granite, where values up to 400 counts/s can be encountered.

The same problem can occur on roads, where tarmac roads of identical appearance can show a variation in count rate for the monitor described above that can easily reach a factor of three. Similarly, on a large site, large variations are possible in paving slab material. Even within apparently homogeneous buildings, bricks from different sources can be used, with the footings made from one type of brick and the walls from another.

Background values also depend on material and thickness. Metal and plastic have negligible activity values, while plasterboard, ceramics and stone may have elevated values. It is important to find samples of each of these materials in approximately the same thickness. The background can normally be assessed by finding an uncontaminated sample of each material that is likely to be clean. For example, if dealing with a concrete wall, cutting in 20 mm into an uncracked surface exposes a surface that is likely to be clean, and the activity concentrations of radionuclides attributed to background or the background count rate can be determined from this surface.

4.3.2. Influence of background activity on measurements

The expected background count rate for each monitoring system employed and for each material is important information for clearance (or exemption) measurements as these values enter into the calculation of minimum detectable contamination.

The presence of natural alpha activity may cause concern because material such as granite may contain high levels of natural radioactivity. It is possible that glazed tiles with elevated alpha activity can be encountered, as uranium was a popular colorant for tiles. Such tiles would typically be removed as a part of the decommissioning process. A problem with alpha monitoring is the quite high level of natural activity, up to 3 Bq total alpha/g in building material. Additionally, some components of the uranium and thorium decay chains have high alpha energies, which will further enhance the background count rate, as the range of their alpha particles is greater.

Another possible contributing factor is the potential for natural beta and gamma to be present in the material under examination, for example, ^{40}K in glass. If a large area beta surface contamination monitor is placed on a sheet of glass, the count rate will be slightly elevated above the free air background. Material such as brick can also contain significant quantities of ^{40}K, along with uranium decay products. Most gamma monitoring equipment will be influenced by natural activity in the material to be monitored, by activity values in other material nearby, and by the self-shielding effect of the material to be monitored.

Beta monitors are also susceptible to gamma background radiation, which means that it is not only the surface layer that is contributing to the background signal. Thicker materials have a higher background count rate, up to a material thickness of approximately 200 mm if the material has a significant gamma component.

More specific considerations are applied to material such as concrete and road material where the background activity concentration is highly variable:

- For *concrete*, except where activation has taken place, it is unlikely contamination from the practice is uniform. Concrete is also generally thick enough to shield out the natural background from the far side. It is often necessary to use a hand held gamma spectrometer or remove a sample for laboratory analysis to confirm that the activity concentration of the potential contaminants meets exemption or release levels.
- *Road material* follows the same logic. If the count rate is uniform over a large area, then gamma contamination is likely to be negligible. Again, a sample can be removed for more detailed analysis. One likely scenario is to find a patch in a road that is more active than the remainder of the roadway.

It is sometimes difficult to decide whether it is contamination from a spill or, merely, that the road has been patched with a material with a higher activity. A classic example of the latter is the use of slag from metal smelting which can often have enhanced concentration values of ^{226}Ra, up to 3 Bq/g [31]. The best approach may be to remove the material if there are only limited areas of this nature. The shape of the enhanced count rate is often a good indicator. A strip, which runs across a road in a straight line indicates a pipe or cable trench. In situ gamma spectroscopy or sample analysis provide definitive answers.

4.4. DETECTION SENSITIVITIES VERSUS ESTABLISHED LEVELS

Demonstration of compliance with established levels requires more than showing that contamination is below the detectable limits of the instruments. The monitoring technique also affects the detection of contamination. It is important to demonstrate that the selected instrument and monitoring technique used has a minimum detectable activity (MDA) less than the established activity concentration values. More precisely, the instrument and monitoring technique together need to be capable of demonstrating, with an acceptable level of confidence, that the material being monitored meets these levels.

The ready availability of instruments and techniques that have been used for routine operational monitoring may seem to be an easy and inexpensive solution for this task. Unfortunately, in many cases, these instruments and techniques might not be adequate to the task, since typically acceptable values for clearance are lower than operational values. This difference may mean that the current instruments in use in the area are inadequate for use in the clearance process.

The use of more sensitive equipment for clearance purposes can be achieved by using larger area probes. The use of thinner probe windows to improve sensitivity may not be productive, particularly if there is a mix of radiation types. The significant portion of the signal will normally be provided by the more penetrating radiations where changes in window thickness have little effect, and any improvement for the lower range radiations could well contribute little to the signal as these radiations are the most easily attenuated by surface dirt. Where routine monitoring has employed thin walled Geiger–Müller detectors, which have typical thicknesses of 20–40 mg/cm^2, there may be advantages to selecting detectors (Geiger–Müller, proportional or scintillation) that have a window thickness in the range of 2–5 mg/cm^2.

4.5. ALPHA, BETA AND LOW ENERGY GAMMA RADIATION EMITTERS

Monitoring generally assumes that the contaminant is present as a thin layer on the surface of the material. However, there is an additional complication if the activity is not homogeneously distributed on the surface of the substrate. If the activity is distributed over the surface of particles, a small volume of activity will cover a large area. This contaminant will form an efficient source, with about 50% of the alpha particles escaping outwards. This ideal geometry provides a relatively easily measurable condition. Consider, however, that the same activity could be entrained in a single particle rather than a surface coating over many particles. Only the surface of that particle will contribute to the signal; those alphas emitted inside the particle will not be measured because of self-absorption. This is a challenge to monitoring as it could lead to the belief that the levels have been met, which might not be the case.

The actual physical dimension of an individual particle is small. A sphere of plutonium with a diameter of approximately 12 μm would have a volume about 2×10^{-7} cm^3 and an activity of up to 7000 Bq, most of which would be non-detectable due to self-absorption. Perhaps less than 200 Bq of this activity would be detectable. Therefore, even a very fine powder of pure plutonium compound on a surface will not represent an efficiently detected source.

In other words, as soon as a fragment has a diameter which corresponds to a significant fraction of the range of an alpha particle, then self-absorption takes place. This effect is important even for small particles.

In a similar way to alpha monitoring, the presence of contamination in fragments can lead to a significant underestimate of activity if the fragment dimensions exceed the range of the beta particle. For low energy beta emitters, this effect is pronounced; for higher energy beta emitters, the effect is less important, e.g. ^{90}Sr and ^{90}Y particles 100 μm in diameter will be efficiently monitored.

The significance of this observation is that for alpha and low energy beta contamination, the surface to be monitored needs to be clean of dust, dirt, grease and grime.

4.6. MONITORING OF ROUGH, IRREGULAR OR OTHER TYPES OF SURFACES THAT ARE DIFFICULT TO MEASURE

A critical consideration in surface monitoring is the ability of the radiation of interest to reach the sensitive volume of the detector. This is particularly important for alpha radiation, which has a very short range, on the order of

5 mg/cm^2. Taking into account the detector window thickness and the fact that some energy must be deposited in the sensitive volume, an alpha particle cannot pass through more than about 3 mg/cm^2 and be detected. Surfaces that have been painted after contamination, or are dirty, greasy or dusty, are poor surfaces for monitoring alpha radiation. Other poor surfaces include porous surfaces such as wood, cloth, carpet and unsealed concrete (see Table 5). Surfaces that have been roughened also reduce alpha and beta detection efficiency. These surfaces need to be stripped back to a clean surface by bead blasting, scabbling or other techniques.

Where surfaces have been changed, typically in old buildings, it is normally necessary to remove the sealed surface and monitor underneath, as contamination might have reached under the surface cavity and penetrated plaster or concrete. An example of this is tile or linoleum floor coverings. This surface is often a poor surface, which can well be absorbent, rough and cracked, and with a high natural activity level. The surveyor is, thus, confronted with a surface with a potentially higher background and which could also damage the instrument probe due to surface roughness. This type of material may be better assessed through volumetric measurements in Bq/g rather than Bq/cm^2.

Acceptable surfaces that are used in areas where contamination is expected include stainless steel, aluminium, surfaces smoothly sealed before contamination, glass and plastic composition faced boards. Suitable surfaces can be defined as those where absorption of contamination within the outer layer is low. Similar considerations apply to low energy beta emitters, such as ^{3}H, ^{14}C and ^{241}Pu. Measurement of higher energy beta emitters, such as ^{90}Sr + ^{90}Y can tolerate thin coverings (less than about 20 mg/cm^2), provided a correction factor is used. Table 5 illustrates the influence of surface coatings on the measurement of surface activity [28]. The transmission factors were measured using an appropriate contamination monitor mounted 3 mm above the coated surface. For low energy X ray and gamma radiation, the above list of acceptable surfaces can be extended to waxed floors and polished benches due to the more penetrating nature of the X ray and gamma radiation. For higher energy radiations, material with a significant absorbing layer can be monitored. The main criterion is that the thickness of the absorbing layer needs to be less than 20% of the half value layer for the material and radiation of interest.

4.7. MONITORING IN UNUSUAL PLACES

During facility operation, the majority of monitoring activities is performed on obvious and easy to access surfaces, such as floors, benches and glove boxes. When preparing for the clearance of a building, the furnishings are often

TABLE 5. INFLUENCES OF COATINGS ON CONTAMINATION MONITOR PERFORMANCE [28]

Nuclide	Emission	Transmission (%)								
		Car paint, one coat (2.6 mg/cm^2)	Anti-rust paint (2.6 mg/cm^2)	Lacquer, one coat (2.5 mg/cm^2)	Wood varnish, one coat (1.4 mg/cm^2)	Furniture polish, two coats (0.1 mg/cm^2)	Lubricating oil from saturated cloth (1.3 mg/cm^2)	Lubricating oil, wiped off (0.14 mg/cm^2)	Grease, from saturated cloth (1.8 mg/cm^2)	Grease, wiped off (0.12 mg/cm^2)
^{238}Pu	a	10	0	10	30	90	30	90	20	90
^{14}C	low β	50	50	50	60	95	70	95	60	95
^{36}Cl	medium β	92	88	88	95	100	95	100	95	100
^{90}Sr + ^{90}Y	high β	95	93	95	100	100	100	100	100	100
^{55}Fe	5.9 keV X ray	30	35	50	70	97	70	95	60	95

removed, revealing parts of the building that were normally concealed. These include drains, ventilation ducts and cable trunking, some of which could have been long disused and might not have been monitored for years. These materials will need to be monitored, either because some are to be left in place for the future use of the building as an uncontrolled area or because they are to be removed for reuse or disposal. There are several difficulties associated with monitoring these types of materials in old buildings:

- It will be necessary to use quite different monitoring equipment to determine contamination from historical practices in the building as the radionuclide spectrum has been modified by radioactive decay. Due to decay time, this can sometimes reduce the easily monitored component, such as ^{60}Co, an energetic beta emitter, while leaving the level of ^{239}Pu, an alpha emitter, relatively unchanged.
- The ingrowth of certain radionuclides may make monitoring easier, such as with the decay of ^{241}Pu to ^{241}Am. This radionuclide produces alpha particles of virtually the same energy as ^{239}Pu, but has the advantage of generating

more than 20 times the number of photons per decay. It also has a much shorter half-life than ^{239}Pu, which means that, mass for mass, ^{241}Am produces more photons. These photons are much more penetrating, with even the low energy, compared to a range of 0.03 mm for the alphas. In unusual areas, which also can be dirty, dusty or have had contamination painted over, the photons at least offer the chance to detect contamination.

For drains, monitoring can be hampered by surface dirt, which can conceal activity. It is a good practice to clean drains and reveal the original surface, which can then be monitored. This is not an easy task, because the surface will probably be curved. For small radius pipes, only relatively small detectors can be used and, if they have flat windows, even they will end up having a window forming a chord across the cross-section of the pipe, which will reduce the response to short range emissions (see Appendix V for a discussion on the loss of response from short range emissions with increasing distance from the surface). The pipe may also have elevated natural activity, on the order of a few Bq/g, which could produce a high background count rate that needs to be considered. Monitoring of such pipes might not be practicable, and in many cases the best option is their removal and disposal.

The problem of dirt on the surface, as raised above, is also relevant to ventilation ducts, conduit and cable trays. For most penetrating emissions, such as gamma rays and energetic beta particles, surface deposits will attenuate the radiation to some degree. It is normally important that final contamination monitoring only takes place on surfaces that are clean.

4.8. NON-HOMOGENEITY

Even perfectly distributed contamination is non-homogenous at the atomic scale. In most instances, material to be monitored will not have a completely uniform distribution of radioactivity. Some parts will be more contaminated than others. In most cases, even when looking at the significantly larger scale of particles, ranging from micron to centimetre sizes, the material to be monitored will be non-homogenous. Averaging (see Section 2.2.5) allows for this scale of non-homogeneity by allowing comparison of values to a concentration averaged over an appropriate mass, volume or area.

There are two basic aspects associated with non-homogeneity of contamination. First is the problem of non-homogeneity within the averaging mass, volume or area. Second is the problem of non-homogeneity at a scale much larger than the averaging mass, volume or area:

(a) *Non-homogeneity within the averaging mass, volume or area*. This complicates the calculation of the actual average concentration. For example, consider a 200 L drum of crushed concrete, where the monitoring method chosen includes several gamma radiation measurements taken on contact with the side of the drum. If the contamination is essentially homogenous, a fairly accurate estimate of the average concentration can be calculated. However, if one needs to consider the possibility that the contamination is non-homogeneous, the uncertainty on the average concentration calculated from any single measurement is significantly higher. If most of the contamination happens to be directly under the measurement point, the calculated average concentration will be much higher than the actual average concentration. Conversely, if most of the contamination happens to be on the far side of the drum, the calculated average concentration will be much lower than the actual average concentration.

This problem can be addressed in a number of ways including the following:

- Depending on the material, it could be better to homogenize prior to monitoring by physical mixing of the material;
- A larger number of measurements could be taken on the outside of the drum to partially account for non-homogeneity of the material;
- The additional uncertainty associated with non-homogeneity of the material could be estimated and taken into account (likely resulting in the use of longer counting times and/or more sensitive detection equipment to ensure that compliance with levels can be demonstrated).

In the case that non-homogeneity occurs on a scale smaller than the averaging volume, it may be cost effective to locate and segregate the contamination and, subsequently, clearing the remaining volume of material.

(b) *Non-homogeneity on a scale much larger than the averaging mass, volume or area*. Non-homogeneities in the material, which are much larger than the averaging mass, generally do not cause a problem concerning clearance, as the material is monitored either completely or on a statistical basis. The activity can, thus, vary between the batches of material, which are subject to measurements, and the decision to clear the material or to reject it is taken for each batch.

Such non-homogeneities can have a greater effect for exclusion or exemption measurements, in particular for material containing activity of natural origin, as there the number of measurements is generally much smaller than for clearance. Care must then be taken that large scale variations in the activity concentrations are adequately detected.

4.9. MIXED HAZARDOUS AND RADIOACTIVE MATERIAL

Material contaminated with radioactive and other hazardous substances (e.g. radioactively contaminated asbestos insulation) present particular problems. Demonstrating compliance with activity concentrations [2] and surface values for radionuclides can be insufficient to allow free release because of the other non-radiological hazards. It is important that all relevant hazards are recognized and taken into account during monitoring, as it might facilitate disposal by other routes. For this reason, personnel performing the monitoring need to be trained and equipped to work safely not only with the radioactive contamination, but any other hazard present as well. It is also important to involve all relevant regulatory bodies, not just those associated with the radioactive component (see Section 2.7).

4.10. TRITIUM

The greatest difficulty with direct tritium (^3H) monitoring is the short range of the beta particle (only about 1 mm in air). Any covering on the monitored material will completely absorb the beta particles. Tritium is typically found in a chemical form that is highly mobile, diffusing into and out of surfaces. Therefore, a surface can appear clean but can be re-contaminated as tritium diffuses from the bulk of the material out to the surface. As a result, direct tritium surface monitoring is unreliable in most circumstances, so for tritium it is often necessary to use sampling techniques to establish activity concentrations. Instruments for the direct measurement of low energy beta emitters, such as tritium, require special consideration. Historically, two types of detector have been employed for the direct monitoring of tritium contaminated surfaces: the windowless proportional counter and the liquid scintillation counter.

With respect to demonstrating compliance with clearance levels, e.g. Ref. [2], in the case of a mixture of radionuclides that includes tritium, tritium might not be as important as other radionuclides due to the relatively high clearance levels (100 Bq/g), as suggested in Ref. [2].

4.11. CHALLENGES IN CALIBRATION

It is important to understand the conditions under which the instrument was calibrated, the conditions under which the instrument will be used, and the effect that any difference in these two sets of conditions has on instrument readings.

Instruments are typically calibrated under specific and controlled circumstances. For example, most gamma radiation detection instruments are calibrated to read correctly in response to the 662 keV photons from a point source of ^{137}Cs, under conditions of standard temperature and pressure. Depending on the instrument, the radionuclide of interest, the geometry of the source, the temperature, the air pressure and, potentially, other factors, the instrument reading can differ significantly from the calibrated conditions. For example, measurements taken with a single channel analyser and sodium iodide detector can vary by tens of per cent depending on the ambient temperature.

Information on calibration of various types of instrumentation is found in a variety of publications [33–35]. National legislation can stipulate additional requirements.

4.11.1. Calibration of surface contamination monitors

For monitoring of *alpha contamination*, calibration requires that the detector is mounted at a fixed distance above an alpha emitting source, which is generally at least as large as the area of the detector. The emission rate from the source is traceable to national standards. The count rate is then recorded and the performance of the instrument calculated and compared with type test data for the radionuclide in question. Common radionuclides for calibration include ^{238}Pu and ^{241}Am, as well as ^{230}Th, which offers a useful source at a lower energy. The response of the instrument is calculated in counts/s·Bq^{-1}·cm^{2} for the surface conditions anticipated.

Calibration measurements generally include confirmation that the response to large area sources of *beta radiation* of the energy range that the detector is designed to measure and expected to encounter, are close to that specified by the manufacturer. This testing is generally based on sources with effectively no self-absorption and that the response, in counts/s^{-1}·Bq^{-1}·cm^{2} in terms of the probability of detecting a particle emitted by the surface, will be higher than the expected operational response or efficiency, particularly for low energy radionuclides. It is essential that users understand this limitation [34].

For release of beta contaminated material, the detectors need to be operated with as low an energy threshold as possible. For scintillation counters, this translates, in practice, to operation at as high a voltage as possible. This improves the performance for less than perfect sources, such as those covered with a very thin layer of grease. The maximum operating voltage is set at the point where the instrument begins to have an increased background count rate. This setting can only be used where there is a negligible level of beta contamination and only a normal gamma background dose rate. It is important to realize that this setting differs from the normal setting used in operational radiological protection, where most detectors are set up to give a high level of beta rejection. This normal setting leads to a much higher counting threshold energy.

The same approach is used for *X ray and gamma emitting radionuclides* as for beta emitters although available calibration sources are generally limited. Common X ray sources include ^{55}Fe (5.9 keV), ^{129}I (38 keV) and ^{241}Am (13–26 keV and 60 keV). For gamma calibration sources, a number of radionuclides are available, including ^{137}Cs with a 662 keV gamma from its short half-life decay product ^{137m}Ba, ^{60}Co which emits 1173 and 1332 keV photons, and numerous other candidates. One problem is that the photon emission probabilities vary between radionuclides far more than beta sources that are used for calibration and this also applies to many potential contaminants. More detailed discussion on calibration is provided in Appendix III.

4.11.2. Calibration of bulk monitors

Calibration of instruments measuring bulk quantities of material is different from calibration of surface contamination monitors. The radionuclides to be monitored, the type of material, its self-absorption, the level to which the measurement chamber is filled and other considerations must be taken into account. The procedure for calibration is generally complex and is prescribed by the manufacturer of the instruments. Usually, the computer that controls the instrument is used in the calibration procedure. Today, such calibration procedures can be greatly simplified by performing one only for a single radionuclide, such as ^{60}Co, with computer based calculation of all calibration factors for the other relevant radionuclides, such as ^{137}Cs, ^{152}Eu, ^{154}Eu, etc.

4.11.3. Calibration of in situ gamma spectrometers

Calibration of in situ gamma spectrometers with collimators is a complex problem as the calibration depends on the radionuclides to be monitored, on the distribution depth of the activity on the surface and in the volume underneath the surface, on the material type and on many other factors. Today, computer models are available that allow the calibration factors to be calculated from a given radionuclide composition and spatial activity distribution. Details are supplied by the manufacturers of the instruments and/or the manufacturers of the software that is used for calibration calculations.

4.12. SAMPLING

When the assessment of activity concentrations in a material (e.g. a block of concrete) are based solely or partly on measurements of samples, it is important to address several issues in order to ensure that the samples will give the information necessary for a clearance decision. In some cases, measurements on samples and in toto measurements will be used in combination to form the basis for the clearance decision. Some of the issues are discussed below.

4.12.1. Sampling positions

Samples are taken in places where the contamination is known or suspected to be present. If contamination is known to be only on the surface of an object, only samples from the surface itself need to be taken. Usually, the sampling positions are chosen to be at the junctions of a sampling grid. An example of a square and a triangular grid imposed on a surface, where 20 surface samples are required is shown in Fig. 7.

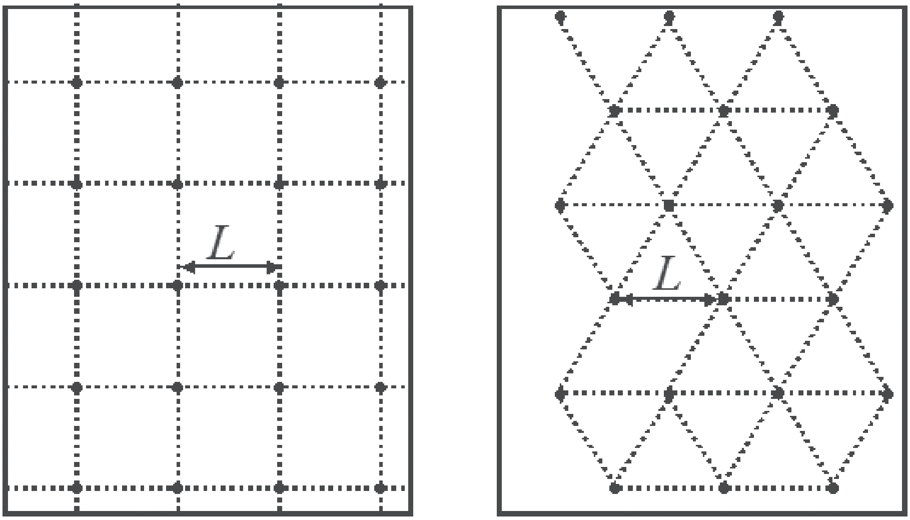

FIG. 7. Example of a square and triangular grid used for sampling on a contaminated surface.

The distance between two adjacent junctions is determined by the total area sampled (A) and the number of samples needed (N). For the square grid, the spacing L is calculated as

$$\sqrt{\frac{A}{N}},$$

and for the triangular grid as

$$\sqrt{\frac{A}{0.866 \cdot N}}.$$

It is important that the sampling position of the individual samples is properly recorded.

4.12.2. Number of samples to be taken

The measurements on the samples are used to obtain information about the activity distribution in the material as a whole for a decision on whether the material complies with the clearance levels or not. Increasing the number of samples gives a better estimation of the median value and the standard deviation of the activity concentration values in the material. The minimum number of samples needed to make a statistical compliance test depends on the median value and the standard deviation of the activity concentration, the statistical test used and the levels put on the decision errors that are used in the test (confidence levels). In some cases, the number of samples has to be increased if as a result of the measured activity concentrations:

- The median value obtained from the sampling is higher than anticipated;
- The standard deviation of the measured activity concentration exceeds a value as determined by the statistical test.

The number of samples needed for the clearance decision raises steeply when the median value is close to the clearance concentration and if the standard deviation on the measured activity concentrations is high.

In the case where the contaminant is (or can be) part of a background contamination (e.g. ^{40}K in neutron irradiated concrete), tests can be performed to take into account the contribution from background. In that case, an equal number of samples from similar background material is also needed.

4.12.3. Minimum sample size

The minimum sample size is inferred from the analytical method(s) that will be used. The sample needs to be able to provide a signal in the detection system well above the detection limit if the concentration of activity in the sample is a significant fraction (greater than one tenth) of the clearance concentration. In this calculation, consideration needs to be given to loss of material in the sample preparation process.

4.12.4. Collection, storage and preparation of a sample

From the collection of a sample to the actual measurement of the activity concentration, care is taken to ensure that the sample activity concentration is not altered (e.g. by cross-contamination or activity loss from the sample). Each sample is weighted, given an ID and stored in a suitable container. If a measurement only requires a sub-sample or aliquot, the sample needs to be homogenized before the aliquot is taken. Any loss of material and/or activity due to preparation of the sample material before measurement must be taken into account. Activity loss can occur through evaporation or volatilization, or through adsorption onto the surface of the sample container. Preservatives are sometimes used to minimize wall deposition effects.

4.12.5. Statistical testing

The decision as to whether to clear a material or not is made by using a statistical test on the measured activity concentrations. Statistical tests vary, and the selection of the proper test may require the assistance of a statistician [36].

In the case of only one radionuclide present in the samples and no background contamination, the null hypotheses states that:

> *The candidate material has a median activity concentration higher than or equal to the clearance concentration* and is tested against the alternative hypothesis which states:
>
> *The candidate material has not been proven to have a median activity concentration higher than the clearance concentration.*

If the distribution function of the activity concentration in the material is unknown, the non-parametric Sign test can be used.

The number of samples needed in a Sign test is given in Table 6 as a function of a normalized median value and normalized standard deviation on the

TABLE 6. NUMBER OF SAMPLES NEEDED IN A SIGN TEST AS A FUNCTION OF MEDIAN CONCENTRATION AND STANDARD DEVIATION OF THE ACTIVITY CONCENTRATION RELATIVE TO THE CLEARANCE CONCENTRATION (DECISION ERROR LEVELS: A = 5% AND B = 10%) [21]

Normalized standard deviation (σ/CL)	Normalized median concentration (m/CL)						
	0.2	0.3	0.4	0.5	0.6	0.7	0.8
0.2	11	11	11	11	12	15	23
0.3	11	11	12	14	17	23	40
0.4	12	13	15	18	23	37	71
0.5	14	16	18	23	32	52	107
0.6	17	18	23	32	47	71	185
0.7	20	23	30	40	71	107	214

activity concentrations. The table values are valid for decision errors where α = 5% and β = 10% (i.e. that the probability is 5% of rejecting the null hypothesis while it is true (Type I error) (believing that contamination is present when it is absent) and there is a 10% probability of accepting the null hypothesis while it is wrong (Type II error) (believing that contamination is absent when it is present).

4.12.5.1. Sign test example

A pile of metal scrap pieces with an almost uniform content of ^{60}Co is a candidate for clearance. Cobalt-60 is the only radionuclide present in the material. Preliminary measurements suggest a median activity concentration of 0.08 Bq/g and a standard deviation of 0.02 Bq/g on the activity concentration in the samples to be taken. Setting the clearance concentration to be 0.1 Bq/g [2] and the decision error levels α = 5% and β = 10%, the number of samples required to make the Sign test is 23 according to Table 6. The results of 23 measurements of activity concentration are:

0.05, 0.05, 0.05, 0.05, 0.06, 0.06, 0.06, 0.06, 0.07, 0.07, 0.07, 0.07, 0.08, 0.08, 0.09, 0.09, 0.09, 0.09, 0.09, 0.09, 0.11, 0.11, 0.11.

The median value is 0.07 Bq/g and the observed standard deviation 0.02 Bq/g. This is in accordance with the assumptions, hence no further samples need be taken. The number of times a concentration value is below the clearance concentration is calculated. This is called the S+ value. In this example, it happens 20 times (S+ = 20). If the S+ value exceeds a certain critical value, the null hypothesis can be rejected. The critical value is a function of the number of samples and the α-value. In this case, the critical value is 15 as shown in the extracted table (Table 7) under N = 23 and α = 0.05, and, hence, the material can be released.

In the case that the contaminant is present, also as background, the null hypothesis is formulated [22]:

> *The candidate material has a median activity concentration that exceeds the median background activity concentration by more than the clearance concentration* which is tested versus the alternative hypothesis which states:

TABLE 7. EXTRACT FROM TABLE A.3 ‘CRITICAL VALUES FOR THE SIGN TEST STATISTIC S+'” [21]

N	a								
	0.005	0.01	0.025	0.05	0.1	0.2	0.3	0.4	0.5
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
21	16	16	15	14	13	12	12	11	10
22	17	16	16	15	14	13	12	12	11
23	18	17	16	15	15	14	13	12	11
24	18	18	17	16	15	14	13	13	12
25	19	18	17	17	16	15	14	13	12

> *The candidate material has a median activity concentration that exceeds the median background activity concentration by an amount that has not been shown to exceed the clearance concentration.*

Tests, such as the Wilcoxon Rank Sum test, can be used in these cases [21]. When the assessment of activity concentrations in a material (e.g. a block of concrete) are based solely or partly on measurements on samples, it is important for the responsible person of the sampling process to address several issues in order to ensure that the samples will give the information necessary for a clearance decision. In some cases, measurements on samples and in toto measurements will be used in combination to form the basis for the clearance decision. Some of the issues are discussed below.

5. EVALUATION OF DATA AND FOLLOW-UP ACTIONS

5.1. TREATMENT OF MEASUREMENT UNCERTAINTIES

Treatment of measurement uncertainties needs to include uncertainty for contamination involving a single radionuclide, and uncertainty for measurement for contamination involving a mixture of radionuclides. The first case relates to measurement uncertainty, and the second case relates to a combination of measurement uncertainty and radionuclide spectrum.

It needs to be noted that the established activity concentration values of Ref. [2] are generally based on trivial potential doses to the public and, therefore, provide significant safety margins.

Monitoring techniques to determine whether established activity concentration values are satisfied rely on the performance of the instrument or the condition of measurement, for example, background level and measurement time. It has to be ensured that the detection limit determined by such factors is sufficiently lower than the activity level required for the clearance judgement and that the measurement has been carried out with appropriate sensitivity and an adequate uncertainty margin.

The treatment of the uncertainty is strongly related to the detection limit. The uncertainty of measurement is generally expressed by a normal distribution. For example, in Japan [37], for a measurement to be considered as exceeding the detection limit, the net count must exceed by three times the net standard deviation of the measurement. In the case of the monitor checked on such a detection limit, the relative error of measurement results is always less than approximately 33.3%, since the measurement results are usually beyond the detection limit. This indicates that an uncertainty of less than approximately 30% is required in the measurement results.

In the United States of America, the concept of detection limit is expressed by the minimum detectable concentration (MDC) [38]. In this case, the detection limit cannot simply be expressed by a factor of the standard deviation, but approximately regarded as 3.29σ, which is twice the value of 1.645σ. (Appendix III). This implies that an uncertainty of less than approximately 30.4% is required in the measurement results, which is the same conclusion drawn in the Japanese concept of the detection limit.

As described above, it can be ensured that the uncertainty of measurements is lower than approximately 30% by complying with the detection limit of measurement. On the other hand, there can be a large scattering of more than an order of magnitude of the radionuclide spectrum of target radionuclides, which can be expressed by a log normal distribution with two parameters, a geometric mean and a geometric standard deviation.

5.2. MEASUREMENT UNCERTAINTIES OF MONITORING TECHNIQUES

The monitoring measurements are inherently uncertain, and, therefore, it is important to consider the sensitivity, or uncertainty, of the technique used for a particular measurement. For a reliable outcome, an appropriate level of uncertainty can be selected in relation to the established values and the anticipated distribution of activity concentration in the material [22].

For illustrative purposes, ^{137}Cs, for which Ref. [2] establishes an activity concentration value of 0.1 Bq/g, can be considered. For this particular case, it is assumed that it is sufficient to show that this level is met, with 95% certainty, for each object monitored for clearance. A technique is chosen which is capable of measuring ^{137}Cs with an uncertainty of 0.02 Bq/g at 0.1 Bq/g (20% measurement uncertainty). For simplicity, it is assumed that the measurement uncertainty of ±0.02 Bq/g is constant in the region around 0.1 Bq/g. Based on preliminary analysis, it has been estimated that the specific activity distribution of the fraction of the material to be monitored is as shown in Table 8.

Figure 8 shows this distribution graphically. The approximately log normal shape, typical of substantially ‘clean’ material (generally a normal distribution), with the addition of a tail to the right due to the presence of the contaminant in varying concentration, should be noted. Reference [39] includes additional examples of the volumetric distribution of some contaminated material.

TABLE 8. ILLUSTRATIVE PRESENTATION OF DISTRIBUTION OF MONITORING RESULTS

Specific activity (Bq/g)	Fraction (%)	Cumulative distribution (%)
<0.05	42	42
0.05–0.06	14	56
0.06–0.07	12	68
0.07–0.08	9	77
0.08–0.09	6	83
0.09–0.10	5	88
0.10–0.11	3	91
0.11–0.12	2	93
0.12–0.13	2	95
0.13–0.14	1	96
0.14–0.15	1	97
>0.15	3	100

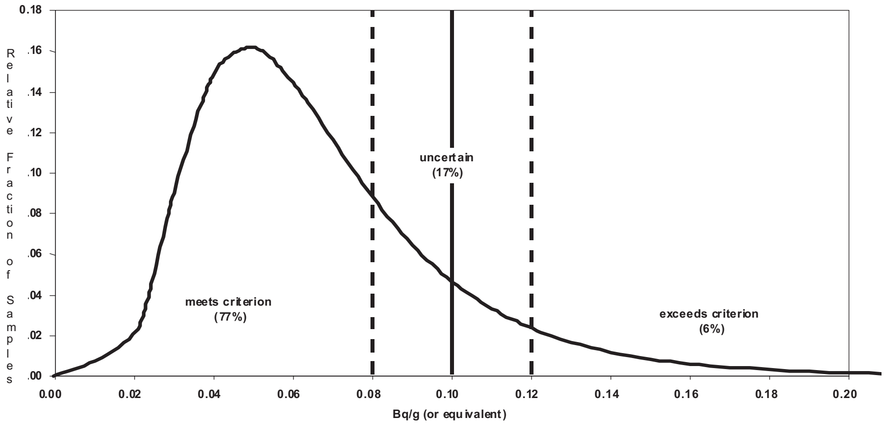

FIG. 8. Activity distribution in relation to an uncertain measurement (Case 1).

Also shown in Fig. 8 is a solid vertical line indicating the clearance level of 0.1 Bq/g. A ‘perfect’ monitoring technique would be able to distinguish with certainty whether any given measurement is above or below these clearance levels. In reality, any measurement of concentration will have an associated uncertainty. The dashed vertical lines in Fig. 8 indicate limits on the uncertainty. Measurements in this section (±0.02 Bq/g) cannot indicate whether or not the clearance level is exceeded with sufficient certainty.

A more sensitive (less uncertain) monitoring technique, perhaps using a longer integrating time or more sensitive instrument, will result in a decreased region of uncertainty (the vertical dashed lines would be closer together).

The fraction of the material which will fall into each of the three categories (meets levels, exceeds levels, uncertain) can be estimated using the anticipated activity distribution of the material and the uncertainty associated with the monitoring technique. Referring again to Fig. 8, these three fractions are equivalent to the area under the curve to the left of the uncertain region (between the vertical dashed lines), the area under the curve to the right of the uncertain region, and the area under the curve in the uncertain region. In this case, approximately 77% of the material is anticipated to meet the levels, approximately 6% is anticipated to exceed them and approximately 17% will be uncertain.

Field measurements equivalent to 0.08 ± 0.02 Bq/g or lower indicate, with sufficient certainty, that the object meets the clearance level of 0.1 Bq/g. Field measurements equivalent to 0.12 ± 0.02 Bq/g or higher clearly indicate that the object exceeds the level of 0.1 Bq/g. Field measurements in the range of 0.08 to 0.12 ± 0.02 Bq/g lie in the uncertain region.

In most cases, without a secondary analysis, material that cannot be shown to have met the levels using a given technique needs to be considered to be above 0.1 Bq/g. In other words, the material meets the criterion or fails. In this example, any field measurement in excess of 0.08 Bq/g indicates a failure, so it is anticipated that 23% [23] of the material will fail.

Reducing the uncertain area by using a more sensitive monitoring technique will reduce the fraction of material in the uncertain region. It is important to recognize that the magnitude of this reduction depends not only on how much more sensitive the technique is (i.e. how much the uncertain area can be reduced), but also depends on the shape of the anticipated specific activity distribution curve in the region of the uncertain area.

In this case, reducing the uncertainty by a factor of two (to ±0.01 Bq/g) will result in a ‘clean’ fraction of 84%, a ‘contaminated’ fraction of 8% and an ‘uncertain’ fraction of 8%. Thus, the uncertain fraction has been reduced by 9% from 17% to 8%.

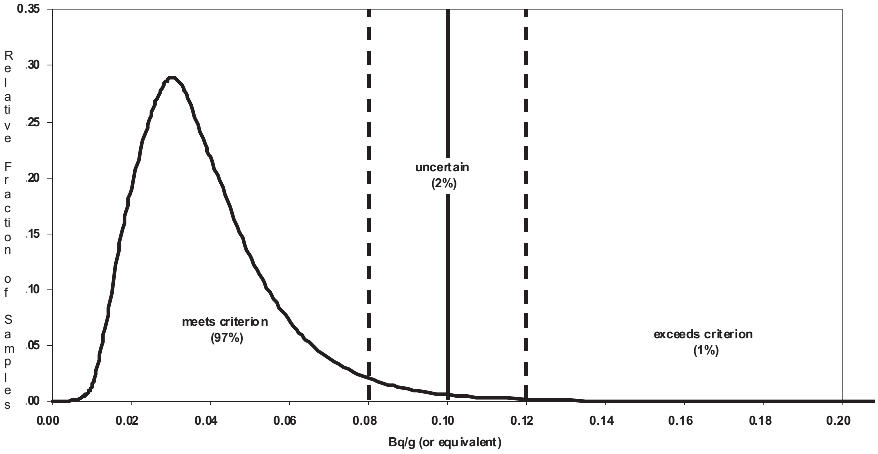

FIG. 9. Activity distribution in relation to an uncertain measurement (Case 2).

Figure 9 can be considered as a comparison. All that has changed from Fig. 8 is the anticipated specific activity distribution. At a measurement uncertainty of ±0.02 Bq/g, the failing fraction is 3%. Here, reducing the uncertainty by a factor of two (to ±0.01 Bq/g) results in a reduction of the failing fraction by only 1.5%.

Equal efforts to reduce the uncertainty had a significantly larger impact in one case (9%) than the other (1.5%).

The principal of diminishing returns tends to apply to the reduction of uncertainty that can be shown in Fig. 9. With an uncertainty of ±0.02 Bq/g, the failing fraction was 3%, and at ±0.01 Bq/g it was 1.5%. If the uncertainty could be reduced essentially to zero (likely at much effort and expense), the failing fraction can only be reduced to about 1%, i.e. that fraction that actually fails the criterion.

Taking into account the uncertain region and its effect on the amount of material treated as radioactive waste, and the costs of various monitoring techniques, one can perform a cost–benefit analysis to compare the utility of each of these techniques. A numerical example of such an analysis is given in Section 3.2.

In this example, only the effects of decreasing uncertainty in a measurement technique on the resulting volume of material that is cleared have been examined. A more comprehensive examination of the problem would also consider the additional cost of the more precise monitoring method with the disposal costs averted by using the method. Section 3.2 discusses this aspect of the problem to a certain extent. Furthermore, were the material treated as a whole for clearance purposes, these curves could result in the clearance of the material based on the average activity and averaging volume as discussed in Section 2.2.5.

5.3. TREATMENT OF UNCERTAINTY FOR MEASUREMENT OF RADIONUCLIDE SPECTRUM

In treating uncertainties due to a mixture of radionuclides, the radionuclide spectrum is applied, meaning that uncertainties in measurement data and ratios of radionuclide concentrations to the key radionuclide concentration are taken into account. To estimate the validity of the uncertainty of the radionuclide spectrum, it is necessary to know the geometric standard deviation that indicates the degree of the scattering ratio of the subsidiary radionuclides to the key radionuclide, after the confirmation of whether the frequency distribution can be fitted to the log normal one.

Reference [2] establishes the value of activity concentration that is equivalent to clearance values for single radionuclides and also shows that the summation (ΣC/CL) of the estimated radionuclide concentration for each radionuclide (C) divided by the clearance level (CL) for each radionuclide has to be less than one to satisfy the clearance criterion for the treatment of a mixture of radionuclides (see Section 2.2.1). It also states that verification of the values is to be based on a procedure that may include direct measurement of a material, laboratory measurements of representative samples and the use of properly derived radionuclide relationships.

For a simple mixture of radionuclides, where there is a clearly defined ratio of the subsidiary radionuclides to the key radionuclide, the uncertainty could be estimated to be the same as that of the key radionuclide. Where the mixture of radionuclides involves naturally occurring and artificial radionuclides, the uncertainty for clearance purposes can be evaluated by individually calculating the uncertainty on the ratio of the key radionuclide and naturally occurring radionuclides, and direct comparison to the level established in Ref. [2]. An example follows. For a key radionuclide a and with natural radionuclides x and y, that have a ratio of R_x and R_y, respectively with respect to a, the following applies: with a ratio to a of R_x and R_y, respectively [35]:

$$C_x = R_x \cdot C_a \tag{5}$$

$$C_y = R_y \cdot C_a \tag{6}$$

$$\sigma_x = \sqrt{C_a^2 \cdot \sigma_{R_x}^2 + R_x^2 \cdot \sigma_a^2} \tag{7}$$

$$\sigma_y = \sqrt{C_a^2 \cdot \sigma_{R_y}^2 + R_y^2 \cdot \sigma_a^2} \tag{8}$$

The treatment of the remaining artificial radionuclides is unchanged.

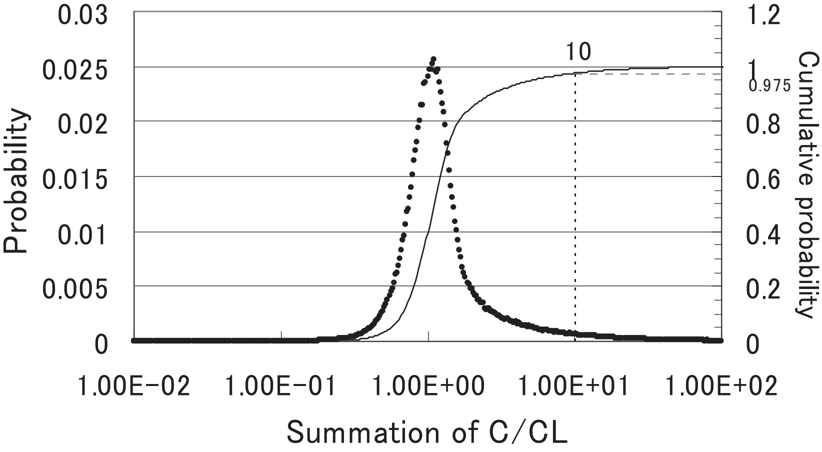

FIG. 10. Probability distribution of ΣC/CL.

In the case of *complex mixtures*, such as those found in a nuclear power plant, the clearance requirement could be that the measurement uncertainty plus the uncertainty due to the radionuclide spectrum cannot be ten times higher than the ΣC/CL, with a 97.5% probability.

Specifically, Fig. 10 shows a probability distribution of ΣC/CL obtained by assuming that:

- A key radionuclide for measurement was ^{60}Co;
- The uncertainty was 30%;
- The distribution derived from measurement of the radionuclide ratio was log normal.

For ^{90}Sr/^{60}Co, the geometric mean and the geometric standard deviation (GSD) were 1.0 and 10.5, respectively. Other radionuclides are taken into consideration using similar approaches. The concentration of ^{60}Co is then normalized, so as to satisfy the relation ΣC/CL = 1, obtained by using a median of C. Finally, a Monte Carlo method, using the information about all applicable radionuclides as input, produces the curve shown in Fig. 10. From Fig. 10, it can be seen that the 97.5% value of ΣC/CL distribution is ten. Thus, the clearance level is satisfied based on the fact that mean dose does not exceed 100 μSv/a, with a 97.5% probability.

Different approaches for treatment of uncertainties related to the radionuclide spectrum are being developed, and an example is the Monte Carlo code prepared for release by the Standard Committee of the Atomic Energy Society in Japan or Central Research Institute of Electric Power Industry [20].

5.4. TOTAL UNCERTAINITY

As discussed in Section 4.2, various types of uncertainties exist in monitoring for compliance of bulk material with established activity concentration values and they all need to be taken into consideration. There are often situations where full monitoring of bulk material is not achievable or practicable. These include material or items:

- That have a complex and extensive shape;
- That are comprised of a mass of heterogeneous material, where activity within the body of the mass is not detectable at the surface;
- Where the radioactivity is not detectable by surface monitoring equipment, for example alpha emitters beneath paint.

The sampling process itself, therefore, needs to be carefully designed because this is potentially a large source of uncertainties. The sampling uncertainty could be assumed to be the standard deviation. For the simple cases of normal distribution, the standard deviation can be calculated using:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}\left(\bar{n} - n_i\right)^2}{\left(N - 1\right)}} \qquad (9)$$

where N is the total number of samples, $\bar{n}$ is the mean of the sample values and n_i are the sample values.

More complex distributions can either be simplified by dividing the monitoring area in several sub-areas or consulting Ref. [40].

5.5. REPRESENTATIVENESS OF RESULTS

In order for the results to be representative of the problem, they have to satisfy several criteria such as:

- The number of samples needs to be sufficient;
- The sampling methods need to be adequate;

- The appropriate monitoring locations have to be selected;
- The monitoring techniques have to be able to characterize the radionuclides to be evaluated.

To be confident in the representativeness of the results, it is important to understand the mechanism that leads to potential contamination being present and to understand any potential chemical or physical influences on the material during and after deposition that may lead to dilution or migration, or concentration of contaminants.

In the case of neutron activation in steel, it is important to know the content of the material that has been exposed. Changes in the alloy may give large changes in the radionuclide ratios in the steel. Where cobalt is present in the steel in a significant quantity, neutron activation will often lead to an easily measured activity of ^{60}Co. This type of measurement would not be adequate if nickel were dominant because the activation product ^{63}Ni produces a low energy beta, which is undetectable by direct measurements except at levels of 10 kBq/g and above. Measurement of ^{63}Ni requires sampling followed by radiochemistry. For pure mild steel, the activity concentrations of cobalt and nickel can be low. The dominant activation product in that case would be ^{55}Fe, which is a low energy X ray emitter (5.9 keV). This, again, is only detectable by direct measurements in relatively high concentrations (1 kBq/g) and has the additional problem that it is impossible to concentrate the material using radiochemistry. Thus, the only monitoring technique able to characterize this radionuclide is the counting of a thin layer of the sample for a very long time.

5.6. VALIDITY OF RESULTS FOR CLEARANCE DECISION

The decision for clearance of material requires approval of the monitoring process and monitoring results.

The monitoring process is usually approved by the regulatory body and it will be the responsibility of the operator to decide whether the material is suitable for clearance based on the monitoring results. A decision as to whether specific material is suitable for clearance is based on evaluation of the monitoring results provided by the operator and, in this case, the regulatory body would base its approval on the monitoring results.

When using an on-line conveyor belt process or a truck monitoring system, there is often a need for an immediate ‘go/no-go’ signal to clear material. Such a process often needs computer processing. This will need to be based on the monitoring results of the material immediately of concern. In other cases, material to be monitored for clearance can be placed in a holding area, which allows review of the results of larger amounts of material monitoring. In the most extreme cases, all of the material needs to be monitored and all results are required before a clearance decision is made based on regulatory body approval.

If staging the material is the preferred option, it is important to gather the material into a controlled area, develop the monitoring plan based on that material, perform the monitoring and evaluation, then disposition that material. No other material is to be added to this controlled area until the monitoring process and disposition are complete.

6. QUALITY MANAGEMENT

Quality management is an integral part of the process for release of material and facilities from regulatory control. The assurance of the quality of results obtained and used during release of material is critical for ensuring and demonstrating that the established activity values have been met.

Quality management provides a disciplined approach to all activities affecting the quality of the decision-making process for the release of material. This includes, where appropriate, verification that each step of the monitoring process has met the objectives and any necessary corrective action has been implemented. It also provides confidence in the use of data, techniques, selection of equipment, selection of monitoring, measurement, sampling, and analysis and interpretation of results. The level of effort put into quality management needs to be commensurate with the scope and complexity of the monitoring process.

Quality management is applied through the whole monitoring process up to the final release of the material. It defines the data quality objectives of the monitoring, which in turn determines, to a significant extent, the required monitoring quality level [41]. Since monitoring results have important regulatory, public health and societal implications, quality management needs to satisfy the recognized standards established by the regulatory body and international standards, e.g. Refs [2, 40, 42].

6.1. QUALITY MANAGEMENT PROGRAMME

A quality management programme needs to be designed and implemented by the operator to ensure that:

- The *relevant requirements and criteria* relating to monitoring are clearly defined and met.
- The *management arrangements* (e.g. organization, roles and responsibilities of managers, and other staff members, competency, detailed instructions and procedures) are in place and have been applied. Depending on the size of the clearance activities (and particularly important for a large project [40]), one of the important steps in developing the quality management programme needs to be for the operator to appoint a qualified professional in the field of quality management, responsible for the development and implementation of a comprehensive quality management programme for release of material from regulatory control.
- An *adequate monitoring strategy* has been reviewed, approved, selected, implemented, and, if necessary, modified, and arguments properly documented.
- *Adequate monitoring techniques* have been selected, reviewed, approved, implemented and, if necessary, modified arguments properly documented. This includes selecting appropriate sampling and measurement methods, frequency, training, etc.
- *Procurement control, including subcontractor services*, is adequately planned and implemented. As exemption or clearance of contaminated material is authorized following the demonstration that residual contamination is less than established activity concentration values, the quality management programme needs to particularly focus on equipment or services directly related to measurement. Capabilities of subcontractors' services need to be evaluated according to established standards [43, 44], for example, laboratory radiochemical analyses or maintenance and calibration of the equipment.
- *Verification and analysis of results* has been undertaken. It needs to be stressed that quality management requirements for release of material from regulatory control particularly need to focus on the verification that the results of all measurements are accurate and reliable to enable the appropriate concentrations to be compared with the established clearance levels. This requires evidence that the samples are collected properly; the correct measurement and analytical methods are employed; the desired accuracy and precision of measurement are reached; the measurement results are assigned to proper material, location, weight, length or sample; and the results are evaluated according to established standards [40].
- *Recording and reporting* procedures are 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 for material release from regulatory control. The quality

management programme needs to emphasize documentation of the calibration, checking and testing procedures, sample management, non-conformity with established levels, and the proper reporting of results. Records of training, including the results of demonstrated qualification, need to be maintained. The achievement of key steps of the material release from regulatory control; of major malfunctioning and unexpected material characteristics (e.g. higher levels of contamination or significantly larger volumes than expected) need to be reported to the project manager, the regulatory body and interested parties (e.g. public) according to established rules and procedures (see also Section 6.3). Also included is the records retention programme that specifies where records will be retained and for what duration.

— *Selection, calibration, testing and maintenance of equipment* is technically based and conducted at specified intervals. This process covers equipment involved in the monitoring activities and the procedures for the operation of the equipment. Where inter-laboratory comparisons or calibrations of monitoring instruments at national or international level have been applied, these also need to be described and results presented.

— *Appropriate qualification, experience and training* of managers and other staff members involved in performing the monitoring activities is ensured. As stated earlier, there are significant differences between radiation measurement in routine operation of facilities and measurement in the context of release of material from regulatory control. Personnel qualified and experienced for routine radiation measurements might not be the best choice for monitoring for release of material. In most cases, staff involved in material release operations require additional training. In particular, the specification of qualification requirements needs to be based on the information collected during preliminary activities about the nature and characteristics of the contamination. Training can then focus on the use of appropriate detectors and on the interpretation of data specific to the material release issues. Periodic re-training of personnel is also required. The extent of qualification and training has to remain commensurate with the complexity of the release operations.

— *Adequate auditing* covering internal and external audits and regulatory inspections is planned and conducted with a view to ensuring that the results are assigned to the correct material, location or sample. Such a procedure needs to include inspection of labelling of samples, field book notations, step by step recording and sample tracking. In this context, the regulatory body could decide to periodically perform (or request the operator to perform) an independent review of the operators' monitoring programmes, including the quality assurance programmes.

- *Measures for identification of non-conformance and adequate corrective actions* are provided. Such control ensures that material which does not conform to exclusion, exemption or clearance requirements is identified and controlled to prevent its unintended use or shipment. When required, corrective actions are taken to eliminate the cause of non-conformities to prevent recurrence, and lessons learned are developed that are subsequently integrated into the training programme.

Quality management needs to be implemented during monitoring for compliance with clearance levels through formally documented and controlled procedures and working instructions.

6.2. SUPERVISION AND RESPONSIBILITIES

For many clearance activities, monitoring could be a long and monotonous process. Human error can become an issue. The quality management system needs to incorporate adequate measures to prevent this from happening. There are various approaches to try to prevent such situations. For example:

- A monitoring supervisor could repeat a fraction of the monitoring at relatively frequent but irregular intervals and the supervisor's results can then be checked against the surveyor's results.
- Use of scaler-timers removes the subjectivity of a ratemeter measurement. Taking a page of monitoring results and performing a frequency analysis would normally show a Gaussian distribution with a slight high-count rate tail. If, on the other hand, some values are present in a statistically unlikely number, it is possible that the monitoring results are not accurate. Availability and access to previous monitoring results need to be known and measures need to be in place to avoid duplication of data in a convincing manner.
- In programmes where a site is being walked to check on the presence of potential hot spots, such as the clearance of radium contaminated sites, then it is sometimes possible that hot spots can be created by burying high natural activity bricks or granite blocks just below the surface. These need to be identified as potential anomalies by the monitoring staff.

6.3. VERIFICATION AND ANALYSIS OF RESULTS

An important part of any monitoring programme to demonstrate compliance with the exemption or clearance levels is the verification of monitoring results. It is an essential element of an effective quality assurance/quality control programme, and helps to gain confidence in the results. Verification of results is normally achieved by:

- Taking duplicate measurements on material;
- Assessing some of the material with more than one monitoring method;
- Having an independent organization monitor a representative sample of the material.

In addition, a qualified expert has to review the data collected on a regular basis, and investigate any unusual or unexpected results.

It is unusual for more than one of the approaches mentioned above to be used. An example is given of monitoring building material contaminated with a high energy gamma radiation emitter. Most of the monitoring is done in bag, box or drum monitors, or by taking integrated readings on the surface of containers with sensitive gamma radiation instruments. Even assuming that this method is sensitive enough to adequately demonstrate compliance with the exemption or clearance levels, it will be necessary to verify the results. This could be achieved by taking occasional representative samples of the material and submitting them for radiochemical analysis. The results of the radiochemical analysis would be compared with the standard monitoring results to demonstrate that the two methods agree. If additional assurance is required or desired, a small number of containers of material (preferably representing a distribution of concentrations in the region of the levels) could also be sent to an independent laboratory for analysis. Once again, the results would be compared to the standard monitoring results to demonstrate that the results agree.

The regulatory body will often undertake its own independent verification programme. This provides added assurance that the monitoring programme is being carried out adequately. However, the verification programme carried out by the regulatory body is not a substitute for the quality control/assurance programme established by the operator or the organization undertaking the monitoring. It is the responsibility of the organization undertaking the monitoring programme to ensure that its results are reliable, and it ought not to rely on the regulatory body to point out unexpected deficiencies in their work. Doing so can be costly as mistakes will not necessarily be corrected as quickly, will likely encourage enhanced scrutiny by the regulatory body, and can affect public perception of the competence of the organization.

6.4. RECORD KEEPING DURING MONITORING

Operators responsible for the clearance activity need to retain key records from the monitoring to demonstrate that clearance has been carried out appropriately. As the release of material will usually not allow further verification of the activity concentration after the material has been released, the safe keeping of proper and sufficiently detailed and accurate records is of particular importance. These records need to be developed and preserved in the appropriate formats.

Records (such as sampling forms and measurement forms; Fig. 11) and final compliance reports) need to be protected from loss, destruction or falsification by storage in access controlled areas or files, and in facilities with appropriate protection against fire and other hazards. Documentation needs to be stored for a defined period of time (approved by the regulatory body, e.g. 5–50 a depending on the history, hazard and characteristics of the material) after the material has been released. Information needs to be recorded for each measurement in sufficient detail to allow anyone reviewing the monitoring programme to identify the exact reason for the measurement and its position. The quality management programme needs to establish a formal document and record management system to preserve this information.

There needs to be a procedure for any measurement obtained during the release of material from regulatory control. This procedure needs to give clear instructions and identify any potential problems, which could be encountered. The procedure needs to clearly describe how the required information, as identified below, will be collected:

- Details of measurement methods;
- Material requirements — i.e. the activity concentration values, in appropriate instant units, for example, for material which is acceptable for release;
- Description of the measurement apparatus along with tolerances;
- Parameter specifications;
- Preparation of the equipment before initiation of the monitoring;
- Calibration requirements of the monitoring equipment;
- Analytical procedures and standards used;
- Precision of the method, detection limit, measurement uncertainty, repeatability and reproducibility of the results, e.g. for 95% confidence interval;
- Potential hazards to operators;
- Any personal protection measures which need to be used while making the measurements;
- Forms to be used (Fig. 11);
- Details of records to be kept.

Date……

Measuring Certificate No……

A	**Relevant radionuclides**			
	Reference to the initial characterization of the material			
B	**Clearance levels**			
	Averaging mass [kg]		Activity concentration [Bq/g]	
	Averaging area [cm^2]		Surface contamination [Bq/cm^2]	
	Reference regulation/Documents (Regulation No., RS-G-1.7, etc.)			
C	**Organization performing measurements**			
	Responsible expert:		Department	
	Address:		Tel: Fax: Email:	
D	**Operator**		Licence No:	
	Contact person:		Department	
	Address:		Tel: Fax: Email:	
E	**Origin of the material**			
	Identification of material/batch:			
	Facility/Premise/Area/Equipment of use			
	Treatment of the material if performed prior to monitoring:			
F	**Type of material**			
	Carbon steel	Cloth	Concrete	
	Austenite	Aluminium	Glass	Glass
	Cable	Plastic	Lead	Others (to be specified)
	Paper	Graphite		
G	**Type of contamination**			
	Bulk		Surface	
H	**Packaging**			
	Container		Bag (plastic, paper, etc.)	
	Drum		Other (to be specified)	
I	**Weight and surface**			
	Net weight [kg]			
	Content			
J	**Measuring method**		Technical basis, Procedure number and revision	

K	**Type of equipment**		Date of last calibration and verification check of the equipment		
	Special provision for equipment use:		Date of next calibration:		
L	**Local background**		[μSv/h]		
M	**Measurements**				
	Dose rate at contact [mSv/h]		Dose rate at 1 m [mSv/h]		
	Total alpha activity [Bq]		Total beta [Bq]		
N	Total beta surface contamination [Bq/cm^2]		Removable beta–gamma surface contamination [Bq/cm^2]		
	Total alpha surface contamination [Bq/cm^2]				
O	Number of samples/measurements				
	Wipe sample measurement value				
	Calculation and evaluation of the wipe sample measurement (including compensation and conversion factors)				
P	**Date of measurement**				
Q	**Conclusions**				
	Below		Above values		
R	**Recommended follow-up actions**				
	Release from regulatory control	*Decontamination*	*Reuse*	Disposal	Other (to be specified)
	If the material exceeds the values the operator is notified by: Name: Tel: Fax: Email:		Date: Operator Contact person: Name: Tel: Fax: Email:		

Monitoring performed by: ______________ Signature: _______________ Date: ________

Technical Review by: _________________ Signature: _______________ Date: ________

Approved by: ________________________ Signature: _______________ Date: ________

FIG. 11. Example of a monitoring certificate.

6.5. COMMUNICATION OF RESULTS

6.5.1. Operator to regulatory body

Communication of results to the regulatory body (e.g. those responsible for radiological and non-radiological hazards) is vital to obtaining regulatory approval for the release of material that has been monitored to demonstrate compliance. The Summary Survey Results Report (Table 9) can be the primary

TABLE 9. MAIN CONTENT OF A SUMMARY SURVEY RESULTS REPORT

Summary Survey Results Report	
Executive summary	
1.	Background
	1.1. Scope of project 1.2. Reason for clearance 1.3. Regulatory/legal issues
2.	Material description
	2.1. Inventory and description of material 2.2. History of material 2.3. Identification of site streams
3.	Clearance objectives
	3.1. Established for exemption or clearance levels 3.2. Possible disposition(s) of the material
4.	Clearance strategy and techniques
	4.1. Management approach 4.2. Compliance monitoring strategy 4.3. Monitoring techniques 4.4. Personnel qualifications
5.	Results
	5.1. Monitoring results 5.2. Comparison of monitoring results with levels 5.3. Actual final disposition(s) of the material 5.4. Environmental monitoring and dosimetry results
6.	Lessons learned
	6.1. Major malfunctions and other unexpected occurrences 6.2. Significant changes during operation 6.3. Suggestions for future improvement
7.	References
	7.1. Applicable regulations and standards 7.2. Technical documents 7.3. Procedures
8.	Contributors to the report

vehicle for this communication. The regulatory body can also require or request copies of the records that have been summarized and referred to, but not included in, the Summary Survey Results Report. The regulatory body will be particularly interested in ensuring that the release process has been well documented, and that the basis for the final disposition of all of the material (i.e. compliance with the established levels) has been well justified.

6.5.2. Communication between regulatory bodies

It is encouraged that regulatory bodies coordinate their activities, share their concerns, and communicate their regulatory strategies and their implementation in order to build confidence. This can be accomplished through transparency, disclosure and use of international standards and procedures [2]. This is particularly important when dealing with transport of material across national borders.

6.5.3. Operator to other interested parties

Interested parties other than the regulatory body will also be interested in the information contained in the Summary Survey Results Report. These parties need to be identified early in the monitoring for the clearance process, and can include:

- Owners of the material prior to the release from regulatory control;
- Receivers of the material after release from regulatory control;
- Members of the public;
- Environmental organizations.

These interested parties have various interests. However, a common concern is whether the material cleared from regulatory control is ‘safe’ for any use, and that material cleared for spent recycling or reuse is ‘safe’ for the specified use. Additionally, there may be interest in the disposition of material not cleared.

6.5.4. Operator to other practitioners

An effective and efficient monitoring for release from regulatory control is a complex process. The possible combinations of material types, radionuclides and contamination histories are almost endless, each one being best served with a slightly different set of monitoring techniques. Experience with past clearance projects is invaluable in trying to determine the best monitoring strategy and monitoring techniques. Therefore, effectively communicating lessons learned, both positive and negative, from such projects is essential in ensuring successful future clearance projects. The review of a Summary Survey Results Report can be valuable to others who consider undertaking a similar clearance project. It is vital that results of material release projects (with information on how to obtain the Summary Survey Results Report for more information) are published in the literature and presented at conferences for practitioners of clearance projects.

6.5.5. Summary Survey Results Report

The primary purpose of the Summary Survey Results Report is to provide convincing evidence that the monitoring results support the release of material from regulatory control and there is compliance with the established clearance or exemption levels (e.g. Ref. [2]). It summarizes the results and conclusions regarding which material did and did not meet the levels, and the final disposition (e.g. clearance, retained as radioactive waste) of the material. This report could be developed as part of an overall final survey report of a decommissioning project or as a separate document.

The audience must be considered in preparing the Summary Survey Results Report. The report must also be satisfactory to the owners of the material, the receivers of the material, and the regulatory body. It will also have to meet the needs of other previously identified interested parties.

The Summary Survey Results Report needs to include the elements summarized in the following model table (Table 9) of contents. Each point is discussed in further detail:

(1) Background
  - The reason for undertaking the material release project;
  - A description of the scope of the material release project;
  - A description of regulatory/legal issues including licensing issues;
  - The names and affiliations of the principal personnel involved in the project;
  - The location(s) and dates during which the project was undertaken.

(2) Material description
  - An inventory of all material monitored for release from regulatory control;
  - A summary description of the characteristics of the material monitored for clearance, including radiological characteristics (e.g. radionuclides present, distributions or ranges of radionuclide concentrations, particular radiological 'radionuclide spectrums' and the basis for any used to demonstrate compliance with clearance levels), physical characteristics (e.g. material forms and types, volumes or masses), ownership and other relevant characteristics (e.g. chemical or physical hazards);

- A summary description of the history of the material monitored for clearance, including, where applicable, results of previous remedial work, manufacturing information, discharge information, and information on accidents or incidents, such as spills, that potentially affect the material.

(3) Objectives (exemption or clearance)

- A description of the levels used with concentration limits and averaging areas, volumes or masses, including a full justification for their use, a description of related consultations undertaken with the various interested parties, and evidence of approval of the levels and technical approach by the regulatory body;
- A description of the possible final dispositions of the material (e.g. specified restricted release, retained as radioactive waste).

(4) Strategy and techniques

- A summary description of the management approach applied to the material release project, including a description of the management structure, quality management practices used, and the results of any quality management audits;
- A description of the monitoring strategy used, including a description of alternate strategies considered, a justification for the selected strategy, and a description of related consultations undertaken with the various interested parties;
- A description of the monitoring techniques used, including descriptions of the instruments used, references to procedures, and justifications of derived limits used for comparison with instrument readings taking into account relevant uncertainties;
- A summary of and references to records demonstrating required personnel qualifications, including training records.

(5) Results

- A summary of and references to records of monitoring results, including measurements taken: to demonstrate compliance with levels, of background areas, of standards or duplicates taken for quality control purposes, and for calibrations and instrument function checks;
- A summary of the comparison of monitoring results with levels;
- A summary of and references to records demonstrating the final disposition (e.g. clearance, specified restricted release, retained as radioactive waste) of all material monitored for compliance with levels;
- A summary of and references to records of environmental monitoring results;
- A description of all independent verification results.

(6) Lessons learned
- A description of the positive results, major malfunctions and other unexpected occurrences, such as encountering unexpected activity contamination, unexpected volumes of material to be monitored, variances from expected radionuclide spectrums;
- A description of any significant changes to the scope, levels, management approach, monitoring strategy or monitoring techniques made during the implementation phase of the project, including evidence that changes were made within a quality management framework, and justification for the changes;
- A description of other lessons learned, including suggestions for improvement that might prove helpful for someone else undertaking a similar project in the future.

(7) References
- A list of the regulatory drivers;
- A list of the international and national standards used in the development of technical bases;
- A list of the technical documents used as a basis for the monitoring and sampling strategy and approach;
- A list of the procedures used throughout the process.

(8) Contributors to the report
- The names and affiliations of the authors, reviewers and approvers of the report.

APPENDICES

Appendix I provides a table of radionuclides with summary information that could be useful in the development of techniques for monitoring for compliance of bulk material with clearance levels, as specified in Ref. [2].

Appendix II illustrates a simplified approach for monitoring for compliance with clearance levels.

Appendix III discusses, in more detail, the practical issues related to monitoring techniques, such as determination of the MDA, selection of instrumentation, calibration, etc.

Appendix IV focuses on whether to perform direct monitoring (on scale remaining in the pipe) or indirect monitoring (of the scale removed from the pipe). This example also discusses difficulties particular to equilibrium within the ^{226}Ra series, and considerations of averaging mass.

Appendix V and Appendix VI describe some of the difficulties in bulk and surface monitoring of thin and absorbent materials. They also discuss a solution to the problem of monitoring bulk material, and some of the difficulties with this approach.

Appendix VII discusses the issues and approaches to monitoring potentially contaminated wiring cables, but can be applied to other large volume materials that do not have a flat surface.

Appendix VIII describes the direct monitoring of crushed building materials.

Appendix IX discusses the problem of monitoring alpha contaminated piping and conduit.

Appendix X describes the monitoring of unusually shaped objects for beta radiation monitoring.

Appendix XI focuses on the challenges of monitoring objects with absorbed beta contamination.

Appendix XII describes the monitoring of flat surfaces for contamination.

Appendix XIII describes monitoring flat surfaces for low energy beta emitting radionuclides.

Appendix XIV focuses on monitoring of soil contaminated with a gamma emitting radionuclide.

Appendix I

VALUES OF ACTIVITY CONCENTRATION FOR SELECTED RADIONUCLIDES WITH EXPANDED INFORMATION

Table 10 lists the radionuclides with half-lives of more than 1 d for which values have been derived in Ref. [2], as well as naturally occurring radionuclides. It is the intention of this table to provide information on the radionuclides, as well as hints as to which measurement methods can be used to show compliance with clearance or exemption levels.

The following points need to be observed when using the information from Table 10. The decay modes and the primary energy for α or β decay given in the table do not characterize the radionuclides completely. An indication as to the relevance of γ lines can be derived from the column stating the point source dose rate at a 1 m distance as well as from the notes in the last column:

- The measurement methods referred to are only a general selection. More information can be found in Appendix III of this Safety Report. The applicability of a method is indicated as follows:
  - '+': usually well suited;
  - 'o': suitable under certain circumstances, such as low internal shielding, good surface conditions, etc. and, depending on material type, tests for the specific application need to be performed before this technique is applied to the radionuclide in question;
  - '-': generally not applicable;
  - '*': application possible via another radionuclide in the decay chain.
- If for a certain radionuclide no techniques have been recommended, indirect methods, such as sampling and laboratory analysis, can be considered.
- The column 'correlation/fingerprint' gives an indication as to whether the radionuclide in question can be correlated to another key radionuclide or whether it can be used as a key radionuclide (indicated by 'kn') itself. This list is not complete and site specific correlations can be used. '+' indicates usually good correlation, while 'o' indicates that correlation may be poor. If a radionuclide is included in a natural decay chain and there is secular equilibrium in that chain, indication is given that this radionuclide can be measured using the properties of the other radionuclides of this chain.
- The column 'notes' gives hints about the properties and the decay modes. The signs have the following meanings:

b/B	Weak/strong beta emitter
c/C	Low energy/high energy gamma emitter
A	Alpha emitter
SL	Short lived radionuclide, $T_{½} < 10$ d > 1 d
N	Radionuclide can be of natural origin
Name of other radionuclide in brackets	The decay mode is from the referenced radionuclide which is always in equilibrium with the radionuclide in question
C-1	Tritium always needs to be treated separately
C-2	Consider decay in place rather than measure for clearance
C-3	Consider use of the material fingerprint for analysis of this radionuclide

TABLE 10. EXAMPLES OF MONITORING TECHNIQUES IN RELATION TO THE VALUES OF REF. [2]

Radionuclide	RS-G-1.7 value [2] (Bq/g)	Half-life	Primary decay mode(s)	Primary alpha/beta (max.) energy (MeV)	Total probability for detectable alpha/beta particles/ disintegration	Point-source dose rate constant @ 1 m (mSv · h^{-1} · MBq^{-1})	Beta/ gamma surface monitor	Liquid scintillation counter	Alpha surface monitor	Bulk monitor	In situ gamma spectr.	Correlation/ fingerprint	Notes
H-3	100	12.3 a	B-	0.02	1.0	0.00E+00		+	-	-	-	-	b C-1
Be-7	10	53.3 d	EC			9.29E-06	+	-	-		+	-	C
C-14	1	5.7E+03 a	B-	0.16	1.0	0.00E+00	+	+	-	-	-	-	b
Na-22	0.1	2.6 a	EC B+	0.55	0.9	3.62E-04	+	o	-	+	+	-	C
P-32	1000	14 d	B-	1.71	1.0	0.00E+00	+	+	-	-	-	-	B
P-33	1000	25.4 d	B-	0.25	1.0	0.00E+00	+	+	-	-	-	-	B
S-35	100	87.4 d	B-	0.17	1.0	0.00E+00	o	+	-	-	-	-	b
Cl-36	1	3.0E+05 a	B-	0.71	1.0	0.00E+00	+	+	-	-	-	o (Cs-137)	B
Ca-45	100	163 d	B-	0.25	1.0	0.00E+00	+	+	-	-	-		B
Ca-47	10	4.4 d	B-	0.69	0.8	1.58E-04	+	+	-	-	-		B SL C-2
Sc-46	0.1	83.8 d	B-	0.36	1.0	3.16E-04	+	+	-	-	-		B
Sc-47	100	3.4 d	B-	0.44	0.7	2.17E-05	+	o	-	+	+		B C SL C-2
Sc-48	1	43.8 h	B-	0.66	0.9	5.12E-04	+	o	-	+	+		B C SL C-2
V-48	1	16 d	B+	0.70	0.5	4.60E-04	+	o	-	+	+		B C
Cr-51	100	27.7 d	EC		0.0	6.32E-06	o	+	-	-	o		c
Mn-52	1	5.5 d	EC. B+	0.58	0.3	5.43E-04	+	o	-	+	+		B C SL C-2
Mn-53	100	3.7E+06 a	EC	0.00	0.0	0.00E+00	-	+	-	-	-		
Mn-54	0.1	313 d	EC		0.0	1.38E-04	+	o	-	+	+	+ (Co-60)	C
Fe-55	1000	2.7 a	EC		0.0	0.00E+00	o	+	-	-	-	+ (Co-60)	
Fe-59	1	44 d	B-	0.47	1.0	1.79E-04	+	o	-	+	+	+ (Co-60)	B C
Co-56	0.1	78 d	EC B+	1.46	0.2	5.21E-04	+	o	-	+	+	+ (Co-60)	B C
Co-57	1	270.1 d	EC		0.0	4.09E-05	o	o	-	o	+	+ (Co-60)	c
Co-58	1	71 d	EC B+	0.48	0.1	1.66E-04	+	o	-	+	+	+ (Co-60)	B C
Co-60	0.1	5.3 a	B-	0.3	1.0	3.70E-04	+	o	-	+	+	kn □	B C
Ni-59	100	7.5E+04 a	EC			0.00E+00	-	+	-	-	-	o (Co-60)	
Ni-63	100	100.1 a	B-	0.07	1.0	0.00E+00	o	+	-	-	-	+ (Co-60)	b
Zn-65	0.1	244.6 d	EC B+	0.33	0.0	8.92E-05	+	o	-	+	+		B C
Ge-71	10 000	11.7 d	EC		0.0	1.65E-05	-	+	-	-	-		
As-73	1000	80.3 d	EC		0.0	3.78E-05	o	+	-	-	o		c
As-74	10	17.9 d	EC B- B+	0.90	0.3	1.47E-04	+	o	-	+	+		B C

TABLE 10. EXAMPLES OF MONITORING TECHNIQUES IN RELATION TO THE VALUES OF REF. [2] (cont.)

Radionuclide	RS-G-1.7 value [2] (Bq/g)	Half-life	Primary decay mode(s)	Primary alpha/beta (max.) energy (MeV)	Total probability for detectable alpha/beta particles/ disintegration	Point-source dose rate constant @ 1 m (mSv · h^{-1} · MBq^{-1})	Beta/ gamma surface monitor	Liquid scintillation counter	Alpha surface monitor	Bulk monitor	In situ gamma spectr.	Correlation/ fingerprint	Notes
Se-75	1	120 d	EC		0.0	2.32E-04	+	o	-	+	+	o (Cs-137)	C
Br-82	1	35 h	B-	0.44	1.0	4.38E-04	+	o	-	+	+		B C SL C-2
Rb-86	100	18.6 d	B-	1.77	1.0	1.46E-05	+	o	-	o	+		B c
Sr-85	1	65 d	EC			2.05E-04	+	o	-	-	+		C
Sr-89	1000	50.5 d	B-	1.50	1.0	2.21E-08	+	+	-	-	-		B
Sr-90	1	29.0 a	B-	0.55	1.0	0.00E+00	+	+	-	-	-	+ (Cs-137)	B
Y-90	1000	63.9 h	B-	2.27	1.0	0.00E+00	+	+	-	-	-	daughter of Sr-90	B SL
Y-91	100	58.5 d	B-	1.13	1.0	5.40E-07	+	+	-	-	-		B
Zr-93	10	1.5E+06 a	B-	0.06	1.0	0.00E+00	o	+	-	-	-	o (Cs-137)	b C-3
Zr-95	1	64 d	B-	0.40	1.0	1.26E-04	+	o	-	+	+		B C
Nb-93m	10	16.1 a	IT		0.0	1.42E-05	o	+	-	-	-	o (Co-60)	10% X ray @ 16keV
Nb-94	0.1	2.0E+04 a	B-	0.47	1.0	2.65E-04	+	o	-	+	+	o (Co-60)	B C
Nb-95	1	35.0 d	B-	0.16	1.0	1.30E-04	+	o	-	+	+	o (Co-60)	b C
Mo-93	10	3.5E+03 a	EC		0.0	7.96E-05	-	+	-	-	-	o (Co-60)	
Mo-99	10	65.7 h	B-	1.21	1.0	3.05E-05	+	o	-	o	+	o (Co-60)	B c SL C-2
Tc-96	1	4.4 d	EC	0	0	4.90E-04	+	o	-	+	+		C SL C-2
Tc-97m	100	87.6 d	IT		0.0	5.23E-05	-	+	-	-	-		
Tc-97	10	2.6E+06 a	EC		0.0	7.60E-05	-	+	-	-	-		
Tc-99	1	2.1E+05 a	B-	0.29	1.0	1.24E-10	+	+	-	-	-	+ (Co-60. Cs-137)	B
Ru-97	10	70 h	EC		0.0	1.19E-04	o	+	-	-	+		c SL C-2
Ru-103	1	39 d	B-	0.22	1.0	8.97E-05	+	o	-	+	+		B C
Ru-106	0.1	368 d	B-	0.04	1.0		+	o	-	o	+	o (Cs-137)	b C(Rh 106)
Rh-105	10	35.0 h	B-	0.57	1.0	1.59E-05	+	o	-	o	+	o (Cs-137)	B C SL C-2
Pd-103	1000	17.2 d	EC		0.0	6.22E-05	-	+	-	-	-		
Ag-105	1	40.2 d	EC B+	0.00	0.0		-	+	-	-	-		b
Ag-110m	0.1	250 d	IT B-	0.53	0.3	4.47E-04	+	o	-	+	+	+ (Co-60)	B C
Ag-111	100	7.3 d	B-	1.03	1.0	5.33E-06	+	+	-	-	-		B SL C-2
Cd-109	1	1.3 a	EC		0.0	4.98E-05	-	+	-	-	-		
Cd-115m	100	45 d	B-	1.60	0.9	3.43E-06	+	+	-	-	-		B c
Cd-115	10	53.4 h	B-	1.11	1.0	4.07E-05	+	o	-	o	+		B C SL C-2
In-111	10	67.5 h	EC		0.0	1.36E-04	+	o	-	o	+		c SL C-2
In-114m	10	50 d	IT EC		0.0	4.07E-05	+	+	-	-	o		B(In-114) c

TABLE 10. EXAMPLES OF MONITORING TECHNIQUES IN RELATION TO THE VALUES OF REF. [2] (cont.)

Radionuclide	RS-G-1.7 value [2] (Bq/g)	Half-life	Primary decay mode(s)	Primary alpha/beta (max.) energy (MeV)	Total probability for detectable alpha/beta particles/ disintegration	Point-source dose rate constant @ 1 m ($mSv \cdot h^{-1} \cdot MBq^{-1}$)	Beta/ gamma surface monitor	Liquid scintillation counter	Alpha surface monitor	Bulk monitor	In situ gamma spectr.	Correlation/ fingerprint	Notes
Sn-113	1	115 d	EC		0.0	4.84E-05	+	+	-	-	o	o (Co-60)	B(In-113m) C(In-113m)
Sn-125	10	9.5 d	B-	2.35	1.0	4.67E-05	+	+	-	-	o		B c SL
Sb-122	10	64.8 h	B- EC	1.42	1.0	8.22E-05	+	o	-	+	+		B C SL C-2
Sb-124	1	60 d	B-	0.61	1.0	2.88E-04	+	o	-	+	+		B C
Sb-125	0.1	2.8 a	B-	0.30	1.0	1.03E-04	+	o	-	+	+		B C
Te-123m	1	120 d	IT		0.0	5.26E-05	+	o	-	o	+		c
Te-125m	1000	58.4 d	IT		0.0	6.17E-05	-	+	-	-	-		
Te-127m	10	109.5 d	IT B-	0.73	0.0	1.98E-05	o	+	-	-	-		b
Te-129m	10	33.6 d	IT B-	1.60	0.4	2.00E-05	+	+	-	-	-		B
Te-131m	10	29.8 h	IT B-	0.44	0.8	2.45E-04	+	o	-	+	+		B C SL C-2
Te-132	1	3.2 d	B-	0.22	1.0	7.55E-05	+	o	-	+	+		B C SL C-2
Te-133m	10	55 d	IT B-	0.66	0.9	3.69E-04	+	o	-	+	+		B CC-2
I-125	100	60 d	EC		0.0	7.43E-05	-	+	-	-	-		
I-126	10	13.1 d	B- B+	0.87	0.4	1.06E-04	+	o	-	o	+		B C
I-129	0.01	1.6E+07 a	B-	0.15	1.0	3.40E-05	o	+	-	-	-	o (Cs-137)	b
I-131	10	8.0 d	B-	0.61	1.0	7.65E-05	+	o	-	+	+		B C SL C-2
Cs-129	10	32.4 h	EC B+	1.20	1.0	9.73E-05	+	o	-	+	+		B C SL
Cs-131	1000	9.5 d	EC		0.0	3.36E-05	-	+	-	-	-		SL
Cs-132	10	6.6 d	EC B+ B-	0.81	0.0	1.56E-04	+	o	-	+	+		B C SL C-2
Cs-134	0.1	2.1 a	B-	0.66	1.0	2.70E-04	+	o	-	+	+		B C
Cs-135	100	2.3E+06 a	B-	0.27	1.0		+	+	-	-	-	+ (Cs-137)	B
Cs-136	1	13.1 d	B-	0.34	1.0	3.63E-04	+	o	-	+	+		B C
Cs-137 + d	0.1	30.0 a	B-	0.51	1.0	1.075E-04	+	o	-	+	+	kn γ	B C (Ba-137m)
Ba-131	10	11.7 d	EC		0.0	1.24E-04	+	o	-	+	+		C
Ba-140	1	12.8 d	B-	1.02	1.0	4.45E-05	+	o	-	+	+		B C
La-140	1	40.3 h	B-	1.35	1.0	3.42E-04	+	o	-	+	+		B C SL
Ce-139	1	138 d	EC		0.0	5.55E-05	+	o	-	o	+		c
Ce-141	100	32.5 d	B-	0.44	1.0	1.98E-05	+	o	-	o	+		B c
Ce-143	10	33.3 h	B-	1.11	1.0	6.89E-05	+	o	-	+	+		B C SL
Ce-144	10	284.7 d	B-	0.32	1.0	6.30E-06	+	o	-	o	+		B c
Pr-143	1000	13.5 d	B-	0.94	1.0	1.52E-12	+	o	-	-	-		B

TABLE 10. EXAMPLES OF MONITORING TECHNIQUES IN RELATION TO THE VALUES OF REF. [2] (cont.)

Radionuclide	RS-G-1.7 value [2] (Bq/g)	Half-life	Primary decay mode(s)	Primary alpha/beta (max.) energy (MeV)	Total probability for detectable alpha/beta particles/ disintegration	Point-source dose rate constant @ 1 m (mSv · h^{-1} · MBq^{-1})	Beta/ gamma surface monitor	Liquid scintillation counter	Alpha surface monitor	Bulk monitor	In situ gamma spectr.	Correlation/ fingerprint	Notes
Am-242m	0.1	152.0 a	IT			4.95E-05	+	+	-	-	-	+ (Am-241. α_{tot})	B(Am-242)
Am-243	0.1	7.4E+03 a	A	5.28	1.0	8.46E-05	o	-	+	-	o	+ (Am-241. α_{tot})	A c
Cm-242	10	163 d	A	6.10	1.0	1.95E-05	-	-	+	-	-	+ (Am-241. α_{tot})	A
Cm-243	1	29.0 a	A	5.70	1.0	1.29E-04	+	-	+	+	+	+ (Am-241. α_{tot})	A C
Cm-244	1	18.0 a	A	5.80	1.0	1.74E-05	-	-	+	-	-	+ (Am-241. α_{tot})	A
Cm-245	0.1	8.5E+03 a	A	5.40	1.0	1.22E-04	+	-	+	o	+	+ (Am-241. α_{tot})	A c
Cm-246	0.1	4.7E+03 a	A	5.40	1.0	1.55E-05	-	-	+	-	-	+ (Am-241. α_{tot})	A
Cm-247	0.1	1.6E+07 a	A	4.90	1.0	7.22E-05	+	-	+	+	+	+ (Am-241. α_{tot})	A B(Pu-243) C
Cm-248	0.1	3.4E+05 a	A SF	5.10	1.0	1.23E-05	-	-	+	-	-	+ (Am-241. α_{tot})	A
Bk-249	100	321.2 d	B-	0.12	1.0	0.00E+00	o	+	-	-	-	+ (Am-241. α_{tot})	b
Cf-246	1000	35.9 h	A	6.70	1.0	0.00E+00	-	-	+	-	-	+ (Am-241. α_{tot})	A SL
Cf-248	1	334 d	A	6.30	1.0	1.23E-05	-	-	+	-	-	+ (Am-241. α_{tot})	A
Cf-249	0.1	351.0 a	A	5.80	1.0	1.12E-04	+	-	+	+	+	+ (Am-241. α_{tot})	A C
Cf-250	1	13.0 a	A	6.00	1.0	1.21E-05	-	-	+	-	-	+ (Am-241. α_{tot})	A
Cf-251	0.1	900.0 a	A	6.00	1.0	1.16E-04	+	-	+	+	+	+ (Am-241. α_{tot})	A C
Cf-252	1	2.6 a	A SF	6.10	1.0	1.13E-05	-	-	+	-	-	+ (Am-241. α_{tot})	A
Cf-253	100	17.9 d	B-	0.29	1.0	2.08E-07	+	+	-	-	-	+ (Am-241. α_{tot})	B
Cf-254	1	61 d	SF			1.31E-11	-	-	-	-	-	+ (Am-241. α_{tot})	
Es-253	100	20.4 d	A	6.60	1.0	6.92E-06	-	-	+	-	-	+ (Am-241. α_{tot})	A
Es-254	0.1	276 d	A	6.40	1.0	1.49E-04	+	-	+	+	+	+ (Am-241. α_{tot})	A C(Bk-250)
Es-254m	10	39.4 h	B-	0.47	1.0	1.52E-04	+	o	+	+	+	+ (Am-241. α_{tot})	A(Fm-254) B C SL

TABLE 10. EXAMPLES OF MONITORING TECHNIQUES IN RELATION TO THE VALUES OF REF. [2] (cont.)

Radionuclide	RS-G-1.7 value [2] (Bq/g)	Half-life	Primary decay mode(s)	Primary alpha/beta (max.) energy (MeV)	Total probability for detectable alpha/beta particles/ disintegration	Point-source dose rate constant @ 1 m (mSv · h^{-1} · MBq^{-1})	Beta/ gamma surface monitor	Liquid scintillation counter	Alpha surface monitor	Bulk monitor	In situ gamma spectr.	Correlation/ fingerprint	Notes
Naturally occurring radionuclides — Activity concentration values apply independently for each radionuclide [2]													
K-40	10	1.3E+09 a	B-	1.31	0.9	2.21E-05	+	o	-	+	+	kn natural rad.	B C N
Pb-210	1	22.3 a	B-	0.02	1.0	6.80E-05	+	+	-	*	*	U-238 secular eq.	B(Bi-210) N
Bi-210	1	5.0 d	B-	1.16	1.0	0.00E+00	+	+	+	*	*	U-238 secular eq.	A(U) B SL N
Po-210	1	138.3 d	A	5.30	1.0	1.42E-09	*	-	+	*	*	U-238 secular eq.	A N
Ra-223	1	11.3 d	A	5.72	1.0	8.79E-05	+	-	+	o	+	U-235 secular eq.	A C N
Ra-224	1	3.7 d	A	5.70	1.0	2.97E-06	-	-	+	-	-	Th-232 secular eq.	A c SL N
Ra-226	1	1.6E+03 a	A	4.80	1.0	3.27E-06	*	-	+	*	*	U-238 secular eq.	A N
Ra-228	1	5.8 a	B-	0.04	1.0	0.00E+00	+	o	*	+	+	Th-232 secular eq.	B(Ac-228) b C(Ac-228) N
Ac-227	1	21.8 a	B-	0.04	1.0	2.36E-06	o	+	+	*	*	U-235 secular eq.	A(Th-227) b c(Th-227) N
Th-227	1	18.6 d	A	6.00	1.0	1.15E-04	+	-	+	+	+	U-235 secular eq.	A CN
Th-228	1	1.9 a	A	5.40	1.0	2.14E-05	*	-	+	*	*	Th-232 secular eq.	A N
Th-230	1	7.7E+04 a	A	4.70	1.0	1.86E-05	*	-	+	*	*	U-238 secular eq.	A N
Th-231	1	25.4 h	B-	0.29	1.0	1.47E-04	+	+	*	*	*	U-235 secular eq.	B SL N
Th-232	1	1.4E+10 a	A	4.00	1.0	1.85E-05	*	-	+	*	*	Th-232 secular eq.	A N
Th-234	1	24.1 d	B-	0.20	1.0	2.04E-05	+	o	+	-	+	U-238 secular eq.	B C(Pa-234) N
Pa-231	1	3.3E+04 a	A	5.00	1.0	1.01E-04	+	o	+	+	+	U-235 secular eq.	A C N
U-234	1	2.4E+05 a	A	4.77	1.0	2.10E-05	*	-	+	*	*	U-238 secular eq.	A N
U-235	1	7.0E+08 a	A	4.40	1.0	9.16E-05	o / *	-	+	*	o / *	U-235 secular eq.	A c N
U-238	1	4.5E+09 a	A	4.20	1.0	1.76E-05	+	-	+	-	+	U-238 secular eq.	A C(Pa-234) N

Note: A: Alpha; B-: Beta; B+: Positron; EC: Electron capture; IT: Internal transition; SF: Spontaneous fission.

Parameters used:	References used for verification:
Half-life	ICRP-38 [45], http://atom.kaeri.re.kr/ [46], http://ie.lbl.gov/toi/ [47]
Primary decay mode(s)	ICRP-38 [45], http://atom.kaeri.re.kr/ [46], http://ie.lbl.gov/toi/ [47]
Primary alpha/beta (max) energy	http://ie.lbl.gov/toi/ [47]
Total probability for detectable alpha/beta	ICRP-38 [45]
Point-source γ dose rate constant at 1 m	SHLEIEN, B., The Health Physics and Radiological Handbook, Scinta, Silver Spring, MD (1992) [48]

Appendix II

EXAMPLES FOR SIMPLIFIED CLEARANCE PROCEDURES AND FACTORS TO CONSIDER

There are many opportunities for simplification in clearance procedures. Whether a certain step in a clearance procedure would be regarded as a normal or a simplified approach depends on the standards and requirements that the normal clearance procedure has to fulfil. This can vary from country to country and even from one nuclear installation to another. The following list compares steps that can be regarded as belonging to a normal procedure and those where simplifications have been applied (Table 11). The necessary prerequisites which have to be fulfilled for applying these simplifications are also discussed. It must be noted that only certain simplifications are applicable in a given clearance procedure.

When such simplified steps are used, it is necessary to document the prerequisites and clearly describe assumptions appropriately to make the procedure fully auditable and allow tracing back any decisions on clearance.

TABLE 11. EXAMPLES FOR STEPS IN NORMAL AND SIMPLIFIED CLEARANCE PROCEDURES

Step in a normal clearance procedure	Step in a simplified clearance procedure	Prerequisites/assumptions for using the simplified approach
100% of the surface of items should be measured.	Only part of the surface should be measured — relevant for parts with large surfaces such as metal plates or pipes.	Applicable if material is sufficiently homogenous with respect to contamination history and origin. The measurement density can be determined from statistical tests on the basis of representative areas where the mean value and the standard distribution have been determined.
An averaging area of 100 cm² or several 100 cm² for surface measurements should be used.	A larger averaging area (e.g. 1 m²) should be used — relevant for measurements in bulk monitors without 100% scanning of the surface.	Applicable if the activity is distributed sufficiently homogeneously over the volume of the material or if radiological considerations show that this is of no concern and the average surface specific activity is not too near the surface specific clearance levels.

TABLE 11. EXAMPLES FOR STEPS IN NORMAL AND SIMPLIFIED CLEARANCE PROCEDURES (cont.)

Step in a normal clearance procedure	Step in a simplified clearance procedure	Prerequisites/assumptions for using the simplified approach
100% of the volume of items in bulk monitors should be measured.	Only part of the items should be measured — relevant for large material quantities of similar origin.	Similar considerations apply as for surface measurements (see above).
An averaging mass of 100 kg or several 100 kg for measurements of bulk material should be used.	A larger averaging mass (e.g. 1 or 10 Mg) should be used — relevant for building rubble in large quantities.	Applicable if the activity is distributed sufficiently homogeneously over the volume of the material or if radiological considerations show that this is of no concern and the average activity concentration values are not too near the activity concentration values.
100% of building surfaces should be measured.	Statistical procedures for measurements on building surfaces should be applied — relevant for large sections of buildings to be cleared.	Applicable if the contamination history of the building areas is known and there is no reason to believe that there will be large non-homogeneities. This has to be proven by pre-investigations. Usually, floor areas have to be treated separately from wall areas. Large floor or large wall areas can be treated as one entity, and the averaged measurement results can be related to the entire area.

TABLE 11. EXAMPLES FOR STEPS IN NORMAL AND SIMPLIFIED CLEARANCE PROCEDURES (cont.)

Step in a normal clearance procedure	Step in a simplified clearance procedure	Prerequisites/assumptions for using the simplified approach
Separate measurements of surface specific activities with surface monitors and of activity concentration values with bulk monitors should be performed.	Only one type of measurement should be performed, and the result of the other measurement should be calculated using density and thickness.	This is only relevant if separate sets of surface and activity concentration levels must be complied with. Applicable if the activity distribution is sufficiently homogeneous and there is no ‘hot spot’ criterion, and if the material has such a density and thickness that compliance with one type of activity would automatically satisfy the other type of activity.
100% of building rubble should be measured.	Homogenization of the material should be used, and only part of the material should be measured — relevant for large, continuously arising material streams. Suitable samples should be taken, or a mass equivalent taken from the continuous stream should be used.	Applicable if the material arises from similar parts of the site (e.g. from building demolition or from removal of soil from a single site) and if the waste stream is sufficiently continuous so that homogenization is economically viable. The origin of the material needs to be sufficiently homogeneous so that homogenization is not to be regarded as illegal mixing of contaminated and uncontaminated material but only for making sure that aliquot samples can be taken.

Appendix III

PRACTICAL MONITORING ISSUES

III.1. MINIMUM DETECTABLE ACTIVITY CONCENTRATION

When monitoring for compliance with activity concentration values, the MDC is a crucial parameter of the measuring method that is being used. The MDC needs to be well below the acceptable activity concentration values in order to use the method for compliance measurements. The MDC can be calculated from the MDA by dividing by the mass of the object being counted. Counting of sources with known small activity concentrations can show whether the MDC is acceptable. In the general case where the activity is obtained from a number of net counts in the presence of a background count rate, the MDC is calculated as [44]:

$$\mathrm{MDC} = \frac{3 + 3.29 \cdot \sqrt{\mathrm{Rb} \cdot \mathrm{T}\left(1 + \frac{\mathrm{T}}{\mathrm{Tb}}\right)}}{\varepsilon \cdot \mathrm{T} \cdot \mathrm{W}} \tag{10}$$

where MDC is the minimum detectable concentration (Bq/g), R_b is the background count rate (counts/s), T_b is the time used to determine the background count rate, T is the sample counting time, ε is the counting efficiency counts/(s·Bq) and W is the weight of the sample.

MDC values calculated from Eq. (10) ensure that an activity concentration at the MDC level is detected with 95% probability.

Example

Let:

$\varepsilon = 0.01$ counts/(s·Bq)
W = 200 g
$R_b = 3$ counts/s
$T_b = 10\,000$ s

If the sample is counted in T = 500 s, the MDC is calculated as:

$$\mathrm{MDC} = \frac{3 + 3.29 \cdot \sqrt{3 \cdot 500\left(1 + \frac{500}{10\,000}\right)}}{0.01 \cdot 500 \cdot 200} = 0.13\ \mathrm{Bq/g} \tag{11}$$

If the sample is counted in T = 1500 s, the MDC is calculated as:

$$\mathrm{MDC} = \frac{3 + 3.29 \cdot \sqrt{3 \cdot 5500\left(1 + \frac{5500}{10\,000}\right)}}{0.01 \cdot 5500 \cdot 200} = 0.07\ \mathrm{Bq/g} \tag{12}$$

In the case where T = Tb, Eq. (10) is reduced to:

$$\mathrm{MDC} = \frac{3 + 4.65 \cdot \sqrt{\mathrm{R_b} \cdot \mathrm{T}}}{\varepsilon \cdot \mathrm{T} \cdot \mathrm{W}} \tag{13}$$

III.2. RESPONSE OF INSTRUMENTS

The response of an instrument to a surface specific or activity concentration value is deduced from a radiation transport calculation or measurements on standard sources. As an alternative, a correction factor based on radiation type and energy, and on surface type can be applied [22].

(a) Response of a gamma counter to a surface contamination of a mixture of radionuclides:
  (i) The radionuclides and their activity fractions Na in the mix should be identified;
  (ii) The energy and probability for gamma energy should be determined;
  (iii) The angular detection efficiency for each of these energies should be determined;
  (iv) For each energy, the rate of photons reaching the detector within a given spherical angle element per Bq/cm^2 of the radionuclide should be calculated;
  (v) For each energy, the product of angular efficiency and angular photon rate to give the count rate per Bq/cm^2 of each radionuclide should be integrated;
  (vi) The total count rate per Bq/cm^2 of each gamma emitter should be calculated by summing the count rates for the gamma energy lines of the radionuclide;
  (vii) Finally, the count rate per Bq/cm^2 of the mixture should be calculated by summing fraction weighted radionuclide specific count rates.

The count rate equal to a limiting surface contamination can be calculated as [49]:

$$C = \left(\sum_{a} \frac{\mathrm{fa}}{\mathrm{Na}} \right)^{-1} \tag{14}$$

where C is the activity concentration of the mixture at the clearance level, f_a is the fraction of the activity of radionuclide a, N_a is the clearance level of radionuclide a.

(b) Response of a gamma dosimeter to uniform bulk contamination

If material is uniformly contaminated with gamma radiation emitting radionuclides, estimation of the activity concentration is possible using a relationship between the activity concentration and measured gamma radiation values (e.g. exposure rates, dose rates or count rates). This relationship is of the following general form:

$$C = (M - M_B)/(S \times A \times G) \tag{15}$$

where C is the concentration (e.g. Bq/g), S is the sensitivity factor (e.g. µGy/h per Bq/g) for a semi-infinite solid, A is the attenuation or shielding factor (unitless), G is the geometry factor (unitless), M is the gamma radiation measurement (e.g. µGy/h) and MB is the background gamma radiation measurement (same units as M).

The basis for this relationship begins by considering a relatively simple case, that of a measurement taken above a uniformly contaminated semi-infinite solid. Note that, disregarding air attenuation, the distance between the detector and the surface of the semi-infinite solid does not impact the measurement.

The first step is to determine the expected gamma radiation measurement above a semi-infinite solid uniformly contaminated with unit activity of the radionuclide, or mix of radionuclides, of interest. This can be accomplished theoretically or empirically. Generally, theoretical calculations of this ‘sensitivity factor’ (S) are facilitated using commercially available software, such as Microshield, or, in a relatively simplistic way, using the following approach.

The dose rate at the centre of an infinite mass can be calculated simply from the gamma energy per disintegration and the activity per unit mass, as the dose rate throughout the volume will be the same everywhere. It is simply the rate of gamma energy generation per unit mass, converted into the appropriate units. Hence, the dose rate dD/dT (µGy/h) is:

$$A \times 10^3 \times \Sigma E \times 1.6 \times 10^{-13} \times 10^6 \times 3600 = 0.6 \times A \times \Sigma E \qquad (16)$$

where A = activity concentration in Bq/g, 10^3 converts A into Bq/kg, ΣE is the sum of gamma decay energies in MeV, 1.6×10^{-13} converts the decay energy in MeV to J, 10^6 converts to μGy from Gy, 3600 converts Bq to disintegrations/h. For ^{60}Co at 1 Bq/g, ΣE = 2.5 and the dose rate = 1.5 μGy/h.

The dose rate at the surface of this mass would be half that value, ignoring the difference in the gamma energy absorption characteristics between the matrix, e.g. concrete and air. Hence, as a first approximation, the dose rate on the surface of a material is approximately 0.3 × A × ΣE, which, for the example chosen, is approximately 0.75 μGy/h. This approach is good enough to make an approximate estimate of an instrument's performance but is preferably followed up using the approach below.

Empirical results can be obtained using a suitably well known area of reasonable size (both in terms of area and depth), which contains a relatively homogeneous, well known concentration of the radionuclide (or mix) of interest. For most combinations of instrument, solid matrix (typically concrete) and radionuclide, an area of a metre or two in diameter, and half a metre thick, is sufficient. A more precise determination can be made using constructed or commercially available 'calibration pads', either fixed in place or mobile. In the simplest case, the instrument is placed directly on the calibration pad, the response of the instrument is noted and the 'sensitivity factor' is derived by dividing the response by the known radionuclide concentration. References in the literature [44] are available which discuss this in more detail.

The attenuation or shielding factor (A) accounts for any shielding material between the source and the detector. For measurements taken directly on or near the material, with no intervening shield, A = 1. Measurements taken through truck boxes, shipping containers, drums, etc. can have shielding factors in the range of 1 to 0.5 (or possibly lower), depending on the thickness and composition of the shielding material. For example, the shielding factor for the side of a typical 200 L steel drum is approximately 0.8.

The geometry factor (G) accounts for the difference in size, shape and density between the container or object being analysed and a semi-infinite solid, from the point of view of the detector. For measurements taken on contact with and away from the edges of large objects, G = 1. Values <1 are common. For example, G = 0.6 (approximately) for a measurement taken on contact of the middle of the side of a 200 L drum filled to capacity with relatively fine concrete rubble where the radionuclides of interest are the ^{226}Ra series in equilibrium. It should be noted that this factor varies not only with the size of the object, but also with the distance between the object and the detector, the location of the measurement with respect to the object (e.g. near an edge versus in the middle of a face), the density and composition of the solid matrix, and the energy spectrum of the radionuclide(s) of interest. It should also be noted that values >1 (but never >2) are possible. For example, for a measurement taken deep in the centre of a large object (such as down a deep, relatively narrow borehole), $G = 2$.

The background gamma radiation measurement (M_B) is the value that would be measured if the source in question contained none of the radionuclide(s) of interest. It should be noted that this is not the same as the measurement taken in the absence of the object to be measured. M_B also includes the contribution from any other radionuclide(s) in the object (often naturally occurring uranium or thorium series radionuclides, or ^{40}K). It also takes into account any shielding of the ambient gamma radiation field provided by the object to be measured.

An example calculation is given. It is assumed that the object to be measured is a 200 L steel drum filled to capacity with concrete rubble uniformly contaminated with ^{214}Bi and ^{214}Pb with an equal amount of activity (^{226}Ra decay chain). Theoretical and empirical studies have shown that, for this case, the sensitivity factor $S = 0.6$ µGy/h per Bq/g of either radionuclide, the shielding factor $A = 0.8$, and the geometry factor $G = 0.6$. The background dose rate M_B is 0.04 µGy/h and the total measured dose rate M is 0.1 µGy/h. By using Eq. (11), the activity concentration of ^{214}Bi and ^{214}Pb is calculated to be:

$$C = (0.1 - 0.04)\ \mu\text{Gy/h}/(0.6 \times 0.8 \times 0.6\ \mu\text{Gy/h per Bq/g}) = 0.2\ \text{Bq/g} \quad (17)$$

It should be noted that 0.2 Bq/g corresponds to the total concentrations of ^{214}Bi and ^{214}Pb. The clearance level for each is 1 Bq/g and the concentrations are equal, so the activity concentration of each is 0.1 Bq/g. In this example, the activity concentration values (from Ref. [2]) are 1 Bq/g, which corresponds to a measurement of 0.6 µGy/h above background and the material clearly complies.

Depending on the radionuclide(s) and source geometry in question, a relatively low background, a multitude of measurements, and/or long counting times (to increase the precision of the measurements) may be required to demonstrate compliance with clearance levels.

It should be noted that this example is only valid for a homogeneously contaminated source. In practice, this is rarely the case. As a result, multiple measurements on the sides, top and bottom (where possible) of the object in question are taken, concentrations calculated for each measurement (since shielding and geometry factors can differ from measurement to measurement) and a possibly weighted average taken to determine the average activity concentration.

III.3. PROPERTIES OF VARIOUS TYPES OF INSTRUMENTS [50]

TABLE 12. PROPERTIES OF VARIOUS TYPES OF INSTRUMENTS

System	Description	Application	Remarks	Equipment cost (US $)	Measurement cost (US $)
Alpha spectroscopy	A system using silicon diode surface barrier detectors for alpha energy identification and quantification.	Accurately identifies and measures the activity of multiple alpha radionuclides in a thin extracted sample of soil, water or air filters.	Sample requires radiochemical separation or other preparation before counting.	10 000–100 000	250–400
Alpha scintillation survey meter	<1 mg/cm^2 window; probe face area 50–100 cm^2.	Field measurement of presence or absence of alpha contamination on non-porous surfaces, swipes and air filters, or on irregular surfaces if the degree of surface shielding is known.	Minimum sensitivity is 10 counts/min, or 1 counts/min with headphones.	1000	5
Alpha track detector	Polycarbonate plastic sheet is placed in contact with a contaminated surface and kept in place.	Measures gross alpha surface contamination, soil activity level or the depth profile of contamination.	Alpha radiation produces holes that are enlarged chemically. Density of holes gives a measure of the radioactivity level.		5–25

TABLE 12. PROPERTIES OF VARIOUS TYPES OF INSTRUMENTS (cont.)

System	Description	Application	Remarks	Equipment cost (US $)	Measurement cost (US $)
Electret ion chamber	A charged Teflon disc in an open-faced ion chamber.	Measures alpha or beta contamination on surfaces and in soils, plus gamma radiation dose or radon concentration.	The type of radiation is determined by how the electret is employed, e.g. the unit is kept closed and bagged in plastic to measure gammas.	4000–5000	8–25
Long range alpha detector (LRAD)	1 m × 1 m detector measures ionization inside the box; attached to tractor for movement; has location finder and plots graph of contamination.	Measures surface contamination or soil concentration at grid points and plots curves of constant contamination; intended for large areas.	Alpha detection limit is 20–50 dpm/100 cm^2 or 0.4 Bq/g (10 pCi/g).	25 000	80
Gas-flow proportional counter (field)	A detector through which P10 gas flows and which measures alpha and beta radiation; <1–10 mg/cm^2 window; probe face area 50–100 cm^2 for hand held detectors; up to 600 cm^2 if cart mounted.	Surface scanning, surface activity measurement or field evaluation of swipes; serves as a screen to determine whether more radionuclide specific analyses are needed.	Natural radionuclides in samples can interfere with the detection of other contaminants; requires P10 gas, but can be disconnected.	2000–4000	2–10/m^2

TABLE 12. PROPERTIES OF VARIOUS TYPES OF INSTRUMENTS (cont.)

System	Description	Application	Remarks	Equipment cost (US $)	Measurement cost (US $)
Gas flow proportional counter (lab)	Windowless (internal proportional) or window <0.1 mg/cm^2, probe face area 10–20 cm^2; may have a second or guard detector to reduce background and MDA.	Laboratory measurement of water, air and swipe samples.	Requires P10 gas; windowless detectors can be contaminated.	4000–30 000	50
Liquid scintillation counter (LSC)	Samples are mixed with cocktail and the radiation emitted causes light pulses with proportional intensity.	Laboratory analysis of alpha or beta emitters, including spectrometry capabilities.	Highly selective for alpha or beta radiation by pulse shape discrimination; requires LSC cocktail.	20 000–70 000	50–200
Geiger–Müller survey meter with beta pancake probe	Thin 1.4 mg/cm^2 window detector; probe area 10–100 cm^2.	Surface scanning of personnel, working areas, equipment and swipes for beta contamination; laboratory measurement of swipes when connected to a scaler.	Relatively high detection limit, making it of limited value in final status surveys.	400–1500	5–10

TABLE 12. PROPERTIES OF VARIOUS TYPES OF INSTRUMENTS (cont.)

System	Description	Application	Remarks	Equipment cost (US $)	Measurement cost (US $)
Geiger–Müller survey meter with gamma probe	Thick-walled 30 mg/cm^2 detector.	Measures radiation levels above 0.1 mR/h.	Its non-linear energy response can be corrected by using an energy compensated probe.	400–1000	5
Pressurized ion chamber (PIC)	A highly accurate ionization chamber that is rugged and stable.	Excellent for measuring gamma exposure rate during site remediation.	Used in conjunction with radionuclide identification equipment.	15 000–50 000	50–500
Hand held ion chamber survey meter	Ion chamber for measuring higher radiation levels than typical background.	Measures true gamma exposure rate.	Not very useful for site surveys because of high detection limit above background levels.	800–1200	5
Hand held pressurized ion chamber survey meter	Ion chamber for measuring higher radiation levels than typical background.	Measures true gamma exposure rate with more sensitivity than the unpressurized ion chamber.	Not very useful for site surveys because of high detection limit above background levels.	1000–1500	5

TABLE 12. PROPERTIES OF VARIOUS TYPES OF INSTRUMENTS (cont.)

System	Description	Application	Remarks	Equipment cost (US $)	Measurement cost (US $)
Sodium iodide survey meter	Detectors sizes up to 8 in × 8 in; used in micro R-meter in smaller sizes.	Measures low levels of environmental radiation.	Its energy response is not linear, so it needs to be calibrated for the energy field it will measure or have calibration factors developed by comparison with a PIC for a specific site.	2000	5
FIDLER (field instrument for detection of low energy radiation)	Thin crystals of NaI or CsI.	Scanning of gamma/X radiation from Pu, Th and Am.	Fragile crystal typically has a Be entrance window; the probe may need to be enclosed in a thick plastic bag while in field use.	6000–7000	10–20
Sodium iodide detector with multichannel analyser (MCA)	Sodium iodide crystal with a large range of sizes and shapes, connected to a photomultiplier tube and MCA.	Laboratory gamma spectroscopy to determine the identity and concentration of gamma emitting radionuclides in a sample.	Sensitive for surface soil or groundwater contamination; analysis programmes have difficulty if sample contains more than a few isotopes; temperature sensitivity affects location of photo peaks in the spectra.	6000–20 000	100–200

TABLE 12. PROPERTIES OF VARIOUS TYPES OF INSTRUMENTS (cont.)

System	Description	Application	Remarks	Equipment cost (US $)	Measurement cost (US $)
Germanium detector with multichannel analyser (MCA)	Intrinsic germanium semiconductor in p or n type configuration and without a beryllium window.	Laboratory gamma spectroscopy to determine the identity and concentration of gamma emitting radionuclides in a sample.	Very sensitive for surface soil or groundwater contamination; is especially powerful when more than one radionuclide is present in a sample.	35–150 000	100–200
Portable germanium multichannel analyser (MCA) system	A portable version of a laboratory based germanium detector and multichannel analyser.	Excellent during characterization through final status survey to identify and quantify the concentration of gamma ray emitting radionuclides and in situ concentrations of soil and other media.	Requires a supply of liquid nitrogen or a mechanical cooling system, as well as highly trained operations.	40 000	100
Field X ray fluorescence spectrometer	Uses silicon or germanium semiconductor.	Determining fractional abundance of low percentage metal atoms.		15 000–75 000	200
CZT	Cadmium, zinc telluride crystal connected to MCA.	Same as NaI(Tl).	Lower efficiency at higher energy; better resolution than NaI(Tl).		

III.4. MONITORING TECHNIQUE FOR DIRECT MEASUREMENT OF SURFACE CONTAMINATION

(a) Summary of direct surface monitoring instruments and techniques

TABLE 13. SUMMARY OF DIRECT SURFACE MONITORING INSTRUMENTS AND TECHNIQUES

	For alpha radiation	For beta radiation	For gamma radiation and X rays
Instruments	Large area (100 cm^2 upwards). For 0.1 $\mathrm{Bq/cm}^2$, a sensitivity of the order of 20 $\mathrm{s}^{-1}\cdot\mathrm{Bq}^{-1}\cdot\mathrm{cm}^2$ or greater. Audio output. A low threshold energy. Effectively zero background count rate.	Large area detectors (100 cm^2 upwards) are better and offer significant time savings. Energy dependence needs to match the expected contaminants. The detection efficiency for high energy radionuclides is typically 50% of surface emission. The calculation of the response to a complicated radionuclide mix will require care. Audio output. For low energy contaminants, the detector needs to be held within a few mm of the surface but for higher energies can be held further away. Typical background count rates are approximately 0.5–1/s per 20 cm^2 of useful area.	The maximum surface size of the detector is approximately 150 cm^2. Energy dependence needs to match to the expected contaminants. The detection efficiency rises as the energy falls, plateaus at close to 100 keV for sodium iodide detectors and then falls as window attenuation and the effects of the low energy threshold take effect. The calculation of the response to a complicated radionuclide mix will require care, even more so than for beta radiation. Audio output. For very low energy contaminants (5 keV), the detector needs to be held within a few centimetres of the surface but for higher energies can be held further away. This will increase the averaging area but not greatly reduce the response to uniformly distributed activity. Typical background count rates are higher, area for area, than similar sized beta only detectors.

TABLE 13. SUMMARY OF DIRECT SURFACE MONITORING INSTRUMENTS AND TECHNIQUES (cont.)

	For alpha radiation	For beta radiation	For gamma radiation and X rays
Surfaces	• Non-absorbent. • No covering of potential contamination. • Clean dry surface (no dust, grime, oil or moisture).	• For low energies, the surface must be clean, dry, non-absorbent, with no covering of potential contamination. • Clean surface.	• For low energies, the surface must be clean, dry, non-absorbent, preferably with no covering of potential contamination. If covering is present, a correction factor needs to be applied to the instrument reading to determine the activity. • For higher energies (20 keV), surfaces with a thin covering of plastic, for example, can be monitored. • For yet higher energies (60 keV), activity can be reliably detected through paint and a thin aluminium sheet.
Techniques	• Probe no more than 3 mm from the surface. • Relatively slow movement-scan speed in ratemeter mode is calculated based on efficiency, background and clearance level, typically 1 probe width(s). If an audible click is detected, the probe is held in place for a period of time corresponding to a 90% probability of another click if the contaminant of concern is uniformly distributed on the surface at the clearance level, typically 10–15 s. If another click is detected during this interval, the instrument is switched to integrate mode and held in place for a period of time that corresponds to the fraction of the MDC required in the documented procedures.	• Relatively slow movement over the surface or static, integrating measurements. • For areas of suspected contamination, the entire surface is scanned at a calculated scan rate. If there is no discernable increase in count rate based on the scan, a few integrated readings are taken at a statistically determined number of selected random locations and documented.	• Ratemeter mode can often be used but better results will be obtained by using integrated counting over a few (up to 10) seconds. • Movement over the surface in quite large steps.

(b) Alpha radiation

Alpha monitoring is generally employed where contamination by alpha emitters is estimated to comprise more than a few per cent of the total level of contamination. This is because the acceptable activity concentrations for alpha radionuclides are generally one tenth (or lower) of those for beta and gamma emitters [2], caused by the normally higher radiotoxicity of alpha emitters.

Alpha particles have high specific ionizing properties and consequently a short range, typically 5 mg/cm^2. They also have a clearly defined range of energy. The short range and high ionization rate of alpha particles is both a problem and an advantage. The problem comes from the fact that alpha detectors must have very thin windows and be held close to the contaminated surface of interest. In addition, any significant covering of the source by a layer of grease, paint or even moisture will effectively screen the source completely. The advantage is that, in an appropriately designed detector, the very high rate of ionization produces a very large signal pulse per event, which can be easily discriminated against the much smaller pulses produced by beta and gamma emissions.

Typical detectors for direct monitoring fall into three classes. They are:

- Silver activated zinc sulphide scintillation detectors.
- Thin window gas filled proportional counters which normally detect both alpha and beta radiations.
- Silicon diode detectors. These are less common and generally have a smaller surface area than either of the other types, but can discriminate alpha energies to a degree, the effectiveness dependent on the surface of the material being monitored.

Suitable surfaces for monitoring for compliance with established levels are those that are impermeable, clean and non-greasy. Challenges associated with monitoring poor surfaces are discussed in Section 4.6.

Generally, it is undesirable for either the detector or the person operating the equipment to touch the surface of interest. However, final clearance monitoring will generally take place on a surface which has either been cleaned or on which no contamination is likely. It is also important that the detector is held close to the surface (within 3 mm) and is moved slowly and smoothly across the surface. One option is to equip the detector with easily removable feet. The detector can then be rested on flat surfaces directly. The feet need either to be regularly surveyed using another instrument or to be changed whenever significant activity is detected. This approach cannot be used for non-flat surfaces. The same approach can be taken for floor monitoring. A detector, or set of detectors, can be mounted in a wheeled trolley. Only hard, easily cleaned

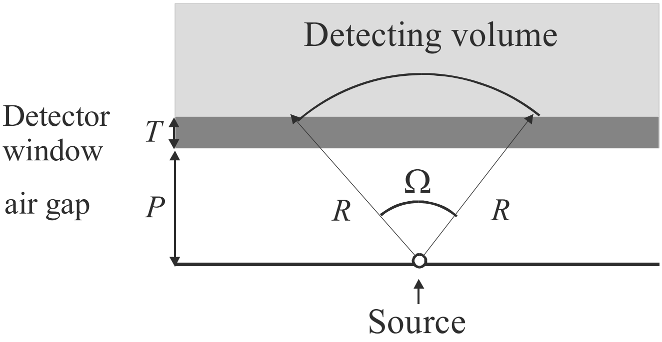

FIG. 12. Example of monitoring of alpha contamination.

material needs to be used for the wheels, and for this reason rubber is not acceptable. Again, the wheels need to be monitored regularly.

The distance from the surface at which the detector must be held is short. In reality, the count rate from a monitor will fall progressively as a detector is moved further away from a source, despite alpha particles having a clearly defined range. An example of monitoring of alpha contamination is shown in Fig. 12.

A detector measures α particles emitted from a point source. The maximum range of the α particles in units of mass per unit area is R. The α particles will only be detected, i.e. reaching the detecting volume, if they are emitted in the solid angle Ω. The ratio of Ω to 2π steradians gives the fraction F of particles detected to the particles emitted away from the surface

Where the air gap P and the window thickness T are expressed in units of mass per unit area, as P increases, F falls progressively.

Scan speed and integrating time

The maximum area which can be monitored per second depends on the ratio of the probe area to the permitted averaging area and on the probe sensitivity in counts $s^{-1}\cdot Bq^{-1}\cdot cm^2$. This assumes that it would be acceptable to have material somewhere in the averaging area which has all the activity permitted in that area, i.e. the activity in the spot = permitted averaging area (cm^2) × limiting average activity (Bq/cm^2). This may not be the case.

A means to calculate the probability of an audible click at a given scan speed when the surface alpha activity is at the clearance level can be found in MARSSIM (Appendix X; [36]).

However, it is often more convincing, at the low activity concentrations expected for residual alpha radionuclides, to perform an integrated count at each location, rather than use a ratemeter in scan mode. Robotics can be considered for large areas that require monitoring in this manner.

The aim needs to be to ensure that there are few false positives, that is areas initially identified as contaminated which are, in fact, acceptable, and very few false negatives, that is areas identified as acceptable which are, in fact, at or beyond the limit. Normal alpha probe backgrounds are very low, but for large area probes, a background count rate of 1/s is assumed. Typically, a low number of false positives will be acceptable as these measurements can be cleared by repeating the count several times. If a counting time of 10 s is selected, the average background count will be 10 counts. On a relatively crude basis, the standard deviation will be about 4 counts. As such, the mean integrated count at the maximum permitted clearance level needs to be about 4 standard deviations above the mean background. If the initial investigation level is set at background + 2 standard deviations, in this case 18 counts or 1.8/s, then the false positive rate will be about 1 in 40 and the level corresponding to the minimum reliably detectable contamination, background + 4 standard deviations, will be about 25 counts or a net 1.5/s. If a 600 cm^2 probe is employed, the detection efficiency for alpha contamination of an otherwise clean surface is about 40% of the alpha surface emission rate. 1 Bq/cm^2 will produce a total of 600 Bq under the detector and a net count rate of 120/s. Using the example above, a 10 s count would reliably detect a net 1.5/s, corresponding to 0.012 Bq/cm^2.

Obviously, a larger detector is easier to damage and is generally more expensive but the maximum identifiable average activity is lower and the time taken to monitor an area is much reduced.

It is important to ensure that the selected instrument and probe combination can detect a fraction of the clearance level, ideally approximately 10% of the clearance level, but no more than 50% of the clearance level, or more detailed analysis is required.

(c) Beta radiation

The beta contaminants encountered in practice can have a very wide energy range, with maximum energies ranging from 18 keV to 3 MeV. Each radionuclide emits beta particles over a range of energies from close to zero up to the maximum, with the average energy being at about 30% of the maximum. The lower energy radionuclides, such as ^{3}H and ^{241}Pu, cannot be monitored directly using detectors with windows and can only be monitored by wiping or using special windowless detectors. The range of lower energy beta particles is much less than that of alpha particles and, hence, they are even more susceptible to source self-absorption. On the other hand, the beta radiation from radionuclides such as ^{90}Y has maximum ranges in air of several metres. For such radionuclides, monitoring of even painted surfaces is possible, provided a correction factor is incorporated (see Section 4.6 for further discussion of monitoring poor surfaces).

Beta detectors have a significant background count rate, generally caused by energetic secondary electrons produced by gamma radiation. It is possible to shield beta detectors using tungsten, for example, but this only shields from radiation incident on the back and sides of the detector and does not significantly attenuate the other main external background source, cosmic radiation.

The minimum detectable beta surface activity is dependent on the maximum beta energy and, hence, on the radionuclide. For the majority of relatively long lived radionuclides, there is a general correlation between radiotoxicity and energy: the higher the radiotoxicity, the easier is detection.

Various detectors are used in the direct measurement of beta surface activity, including scintillation detectors, gas proportional counters of both sealed and gas refillable varieties and thin walled or mica end window Geiger–Müller detectors. Each type of detector has slight advantages over the others depending on the circumstances.

One aspect of beta monitoring, which is often ignored, is the use of a counting energy window, rather than counting all pulses above a defined minimum energy threshold. This is not applicable to Geiger–Müller counters, which produce a pulse, which is independent of the energy of the particle generating the pulse. It is useful for scintillation and proportional counters used for monitoring low energy and degraded higher energy beta emitters. In this case, the low energy threshold is set at the manufacturer’s suggested value for the survey instrument concerned, the window width either switched off or set to maximum, and the plateau established (source + background and background only). The best operating voltage is established, which for low energy beta emitters is normally with the source + background count rate just on the plateau, and then the window width reduced progressively and recorded against the count rate for source + background and background only. The upper limit is then generally set at the point where the net count rate produced by the source is on the point of starting to fall if the window width were to be further reduced. For low energy radionuclides, it is sometimes possible to reduce the background count rate by a factor of four for a negligible change in count rate from the source.

Suitable surfaces

The efficiency of direct beta monitoring depends both on the material and the energy of the beta emitting contaminants. If low energy emitters such as ^{14}C dominate, then the radionuclide spectrum for direct monitoring the surface needs to be impervious and look clean. Monitoring of poor surfaces is discussed in Section 4.6. If the contaminant has a higher maximum energy, such as ^{90}Sr + ^{90}Y, then thin covering layers <30 mg/cm thick can be tolerated, provided a correction factor is employed.

Monitoring techniques

Beta monitoring techniques are similar to alpha monitoring techniques, except because of the higher background, rather than listening for an audible click, the surveyor is listening for an audible increase in the count rate. This is a subjective determination and depends on the training and experience of the surveyor [22].

Generally, it is undesirable for either the detector or the person operating the equipment to touch the surface of interest. However, final clearance monitoring will generally take place on a surface, which has either been cleaned or on which contamination is unlikely. For low energy beta emitters, such as ^{14}C and ^{147}Pm, it is also important that the detector is held close to the surface (within 3 mm) and is moved slowly and smoothly across the surface. For higher energy contaminants, such as ^{90}Sr + ^{90}Y, the detector does not have to be held so close to the surface as the attenuation of the beta particles by 10 mm of air is small. Moving the detector back from a uniformly contaminated surface will have little influence on the count rate.

Scan speed and integrating time

The maximum area that can be monitored per second depends on the probe sensitivity and the ratio of the probe area to the permitted averaging area. In the simple case, the probe response to the maximum permitted clearance level in counts/s is well above the background count rate. For example, the average background might be 5 counts/s and the net count rate at the limiting level might be 10 counts/s. If the user then has a limit of 10 counts/s, indicated by the ratemeter as an initial reaction level, then it is statistically unlikely that the instrument will indicate a false negative. This is based on a ratemeter with a 3 s time constant (T), which at a total of 15 counts per 3 s (N) will have a random fluctuation or standard deviation

$$(\sigma) = \frac{\sqrt{N}}{T}$$

or 1.3 counts/s.

The mean count rate corresponding to the reject level is, thus, approximately 4σ higher than the initial reaction level and, thus, the probability of a false negative for a surface contaminated at the maximum permitted clearance level is less than 1 in every 100 readings, which is tolerable. Similarly, the initial reaction level is approximately 5σ higher than the mean background level and, hence, it is extremely unlikely that monitoring will generate a false positive. The level set also ensures that the average contamination level is <50% of the limit. The monitoring speed can then be calculated as the time which allows the ratemeter to respond to a change in contamination level between clean and an area which is just at the limit. This approximates to two time constants or, normally, about 5 or 6 s. For example, if the averaging area is 1000 cm^2 and the monitor is 15 cm wide, then the maximum monitoring speed is about 3 cm/s. Over 20 s, the probe will move 60 cm, covering a total area of 900 cm^2.

This analysis ignores the use of the audio output. A reasonably skilled surveyor will notice the increase in count rate, find the maximum and pause, allowing the ratemeter to respond to the change. Hence, monitoring speeds can, in practice and for the sort of situation described above, be faster than the calculated value, without missing unacceptable values of contamination.

However, the difference between the background and the count rate corresponding to the maximum permitted clearance level is often much smaller. In that case, it is generally easier to use monitors in an integrated count rather than a count rate mode. The statistical basis is easy to calculate [22]. The aim is to definitively distinguish between values which are acceptable and values which are not. Typically, a low number of false positives will be acceptable, as these measurements can be cleared by repeating the count several times. As such, the mean integrated count at the maximum permitted clearance level needs to be about 4 standard deviations above the mean background. If the initial investigation level is set at background + 2 standard deviations, then the false positive rate will be about 1 in 40 and the false negative rate for contamination at exactly the limit will be the same.

It is assumed that the background count rate, established by a long or multiple measurement, is N/s and the calculated net count rate at the maximum acceptable level is L/s. The standard deviation in a series of measurements for a mean of N/s and a counting time of T s is $\sqrt{NT}$ counts, or

$$\frac{\sqrt{N}}{T}$$

counts/s. What is required is that

$$4\frac{\sqrt{N}}{T} < L$$

Rearranging gives

$$T > \frac{16N}{L^2}$$

As an example, a mean background count rate of 10/s and a maximum acceptable net count = 4/s is considered. Inserting these values into the equation above gives a counting time of 10 s. There is no point calculating the time exactly as counting times on integrating instruments can normally only be set in defined steps.

The best use of this method can be made if the detector area is as close to the permitted averaging area as practical. The larger the detector, the fewer the number of times the detector has to be repositioned to cover any desired area. The larger the detector, the larger is the net count rate from the maximum permitted clearance level, assuming the same window thickness and energy threshold. This will allow the total counting time to be reduced. If, for example, one detector is ten times the area of another, then the number of individual measurements drops by a factor of 10, assuming the averaging area is the same or larger than the probe area. The counting time also drops by a factor of 10. Using the example above, the counting time was 10 s. Extending the area of the detector by 10 gives the following counting

$$\text{time minimum} = \frac{16(10N)}{(10L)^2},$$

which, for $N = 10$ and $L = 4$, equals 1 s. In total, then, increasing the area by 10 reduces the measurement time by a factor of 100.

A practical consideration in the size of the detector has to do with the uniformity of the response of the detector which must be uniform over the face of the detector. Typically, the response at each of a number of check locations on the face of the detector is ±10% of the average of the readings for the detector to be suitable.

The practicality of the monitoring process must also be considered. Moving a large detector takes longer than moving a small one and the chance of damage is higher. The repair cost and the purchase cost are higher. For large flat areas, it makes sense to make use of the permitted averaging area. When using a large area probe, if a reading greater than some per cent of the clearance level is observed, it might be appropriate to scan the area with a smaller probe to find potential 'hot spots'. Use of mechanized systems, including robotics, is useful in moving large detectors and holding them stationary against walls and ceilings during the monitoring process.

(d) Gamma radiation and X rays

Monitoring gamma emitting radionuclides is also important for release of material from regulatory control. Most high energy gamma emitters also emit beta radiation; it is this beta radiation that is generally used to estimate values of surface activity. This is because a beta measurement is essentially a local measurement over a well defined area, whereas the more penetrating nature of energetic gamma radiation means that distant activity can contribute to the count rate. However, there are certain radionuclides for which X ray and γ radiation are best suited for measurement, for example where X ray and γ radiation form a useful alternative to the monitoring of alpha emissions. Americium-241 emits 11–26 keV X rays and 60 keV gamma radiation. Plutonium isotopes also emit 11–20 keV X rays. Another example is ^{55}Fe, which emits a 5.9 keV X ray radiation only.

Two detector types are used in the direct measurement of low energy X ray and gamma surface activity. These are sodium iodide scintillation detectors, and sealed xenon filled thin metal windowed proportional counters.

With some equipment, it is possible to set energy thresholds. For surface contamination, the X ray or gamma radiation striking the detector is mainly unscattered and, for lower photon energies, most of the interactions that take place are photoelectric, with most of the photon energy being deposited in the detector. Hence, it is possible to detect most of the events in the detector by setting up a counting window, which runs from just below the minimum photon energy present in quantity to just above the maximum. This has the effect of reducing the background count rate compared to counting from a minimum energy upwards. The counting efficiency is not affected by setting the window in this manner. The same technique can also be applied for higher energy radiations but the process is somewhat more complicated.

X rays are inherently more penetrating than alpha and beta radiation. However, they can be affected by surface coatings (see Section 4.6 for a discussion of monitoring poor surfaces).

The main difference between monitoring for alpha and low energy beta radiation, and X ray and γ radiation is that air attenuation and attenuation by grease on a surface is much less significant. For X ray and γ radiation >30 keV, air attenuation is trivial at common monitoring heights above the surface. Monitoring can take place with a greater probe to surface separation without air attenuation having a large influence. The main influence of holding the probe further from a surface is to increase the effective averaging area of the probe. As there is no distinct cut off from air attenuation, the averaging area is not well defined. A collimator can be used to define the averaging area but only works well if the detector is held a reasonably long way from the surface, so that the detection efficiency is reasonably uniform over the surface in question. For example, if a value of detection efficiency at the edge of the collimated area equal to 50% of the value at the centre is acceptable, then the radius of the area under investigation is the same as the height above the surface for a detector, which is small, compared to the averaging area. For a typical 1000 cm^2 area, the height is 18 cm. $A = \pi r^2$; for $A = 1000$ cm^2, $r = 17.8$ cm. This height to radius relationship also means that the count rate from the defined area will only be about 30% of the count rate with detector in contact with the surface or for an uncollimated detector. Hence, it is somewhat difficult to use such a system.

If a small averaging area is desired, the detector must be held relatively close to the surface. For a typical detector, with an area of 8 cm^2, a gap of 2–3 cm is acceptable.

Scan speed and integrating time

Determination of optimal probe movement rate follows the same basis as the section for beta measurements but the background count rate is generally higher in comparison with the probe’s response to the contaminants. Large area detectors are also less available. This is compensated for, in many circumstances, by the range of the radiation, which means that detectors can often be held further from the surface in question. The determination of counting times can be performed by considering the area for which the detector response is >50% of the centre response of the monitoring area. For an uncollimated detector with a basically circularly symmetrical response, the probe can be moved in steps equal to the above value divided by 1.4, the square root of 2. This will ensure that all areas are acceptably monitored.

It should be noted that these low energy gamma and X ray detectors can be used in areas where certain alpha contamination activity on walls and other surfaces might have been painted over at some time. This makes direct alpha detection impossible but it is sometimes possible to detect the low energy X ray radiation emitted by many of the Pu and Am isotopes. It might not be possible to detect activity down to typical alpha clearance levels, because the detector background is significant, the probability of the emission of a photon is often low, (4% per disintegration for ^{239}Pu), and the high atomic number component in the paint, normally from titanium or lead, significantly attenuates the X ray radiation. For ratemeter based surveys, this leads to minimum reliably detected values of the order of 10 Bq/cm^2. These instruments are typically used early in the clearance process, where decisions are made on the level of respiratory protection during wall stripping.

It can also seem attractive to use sodium iodide scintillation detectors where there is high energy gamma emitting contamination from radionuclides such as ^{137}Cs or ^{60}Co. These are normally monitored using their beta emissions but, as discussed earlier, these can be difficult to monitor if the surface is dirty. Sodium iodide scintillation detectors are not normally an option, because the background count rate is too high. As an example, the count rate from a 50 mm × 50 mm sodium iodide detector a few millimetres above a circular source of ^{137}Cs with an area of 1000 cm^2 is approximately 12 $s^{-1}\cdot Bq^{-1}\cdot cm^2$, with a background count rate of 50/s. An increase from 50 to 62/s is just on the limit of detectability in circumstances where the background is effectively constant. This should be contrasted with the case for beta detection, where the count rate from a 100 cm^2 detector will be about 50% higher but with a background of 5/s rather than 50/s. The situation can be improved by establishing a window for the detector to reduce the background. In this manner, monitoring the gamma emissions provides a satisfactory technique for surveying the materials.

(e) Monitoring techniques for indirect measurement of surface contamination

(i) Alpha radiation

Direct monitoring of alpha activity is not easy and, in many situations, indirect monitoring is a useful technique. Two ways of performing this include the traditional use of swipes and a more recent technique using a long range alpha detector.

The advantages of using swipes are considerable. However, because the fraction of removable contamination picked up on a swipe is difficult to quantify precisely, it is difficult to achieve precise estimates of surface contamination.

The method is to swipe the surface of interest with a non-absorbent wipe and then count that swipe. Swiping allows access to areas where it would be impossible to place conventional detectors close enough to the surface, including curved surfaces, such as the outsides of pipes, complicated surfaces, such as tap handles and tools, and inside corners of walls. The area to be monitored is generally subdivided into clearly identifiable units and the area of the swipe is estimated. The swipe is then transferred to the counter.

The other advantage is that wiping measures loose contamination, whereas direct measurement measures both fixed and loose contamination. However, for clearance, this differential is probably less important than for workplace monitoring. In the workplace, one of the main aims of surface contamination monitoring is to control the level of resuspended activity. However, during clearance, any significant contamination is unacceptable as reuse of cleared material could easily convert fixed to loose activity, for example by grinding a surface.

Counting alpha swipes

Counting swipes for alpha, generally, uses the same types of detector as those used in direct monitoring: scintillation counters, proportional counters and silicon diode detectors. However, there are several advantages to be gained by collecting and counting swipes. The swipe is placed into an internal counting chamber in the instrument. This gives a well defined and, generally, closer wipe to detector separation. The detector window does not have to be so robust as it is not exposed to the normal stresses of hand held monitoring which means it can be thinner, reducing further the mass per unit area between contamination and the detector element. The instrument can be shielded electrically, which reduces the background values and allows a lower energy threshold. The detector is generally connected to a timer, which permits a long counting period to be set. All of these characteristics greatly improve the probability of detecting an alpha emitted from the surface of the swipe. It is also possible to measure a lower detectable average count rate, as the instrument does not get bored counting for 30 s whereas a surveyor holding an instrument may. It may be possible to make a better estimate of the activity on a swipe than on a surface using a hand held monitor.

Difficulties with the use of swipes, however, include estimating what fraction of the area has actually been swiped and also in estimating the fraction of that activity which has been removed. This can be illustrated by the routine involved in interpreting the wipe:

- It is assumed that the area which has actually been wiped = W cm^2;
- It is assumed that the fraction of the activity which is picked up on the wipe = F;
- The measured activity is determined = M Bq;

$$\text{Average activity} = \frac{\mathrm{M}}{\mathrm{W} \times \mathrm{F}}\ \mathrm{Bq/cm^2} \tag{18}$$

This calculation includes two poorly controlled variables. A careful surveyor can make some sort of estimate of W, for a simple surface. The value of F, however, depends on the surface, the wipe material and the contact pressure. Typically, 10% is assumed, which was based in the United Kingdom in 1955 on an estimated value without any real experimental information and was designed to provide a conservative estimate. Subsequent research has indicated that transfer factors are slightly better than that, and not often worse. Therefore, it continues to be a good value to assume.

The uncertainty in the area wiped and the transfer fraction can be reduced using a small mechanized unit that pops down onto a clearly defined area with a defined contact pressure. It may not be possible to use this technique in areas where swipe sampling is the preferred option.

In a similar way to hand held monitoring, the wiping of dirty or greasy surfaces does not give a good estimate of the removable activity as activity deposited on the wipe will be covered by grease. Dirty swipes do not provide valid results either. Swipe areas greater than approximately 300 cm^2 can lead to redeposition from the swipe.

In summary, counting of swipes for alpha provides a lower MDA. However, the average activity is difficult to determine and if the surface wiped is greasy or dirty, then the build up of grease on the wipe can lead to non-conservative errors.

Counting swipes in a liquid scintillation counter

Counting swipes in a liquid scintillation counter can overcome the problem of grease on a wipe to a great extent. The activity on the wipe will generally absorb into the scintillation cocktail, resulting in the source being dispersed throughout the counting vial and in direct contact with the scintillator. No energy is lost crossing an air gap or penetrating a window. Therefore, a better estimate of the true activity on a swipe sample can be made using a liquid scintillation counter. In fact, analysis of contamination in oil can be performed using liquid scintillation techniques.

The main disadvantages are the cost of the counter, the operating costs (vials and liquid scintillation cocktail) and the delay between collection of a swipe sample receipt of the result. The overall accuracy is still compromised by the uncertainty in the area wiped and the transfer factor.

Long range alpha detection

This technique uses air that is drawn over and through objects, such as pipes and valves, that require monitoring for potential clearance. An object is placed in a sealed box through which filtered air is drawn. Alpha particles generate positive and negative ions in short densely ionizing tracks, a few centimetres in length. Under normal circumstances, these ions recombine but in the turbulent air flowing over and through a pipe under examination, the ions disperse and their rate of recombination decreases. This allows them to survive over a range up to 6 m. The air then passes through an ion chamber, which collects the ions. The resultant current is amplified and displayed. The discrimination against beta and gamma radiation is less than 100%, as in conventional alpha monitors, but is sufficient for use in normal gamma backgrounds. This is because alpha particles deposit approximately 5 MeV in the detector, whereas a typical electron from a gamma interaction will deposit a few hundred keV over a much greater distance. This process allows the detection of alpha activity in excess of 100 Bq distributed over the inside and outside of a full 6 m long pipe or pole.

This technique could be applied to pipes or ducts, which were to be left in a building. One problem is self-absorption in the source, resulting in a low signal per decay. It is important that the surfaces are clean so that loose dust is not blown into the sensing element. If the dust is contaminated it leads to a high background because of the radiation. Inactive dust on insulators causes high, and often erratic, leakage currents, which can disable the instrument until cleaned. Smoke and other sources of ionized air affect the detector, too.

(ii) Beta radiation

Direct beta monitoring can be difficult or impossible in some circumstances because of difficulty of access or the presence of a high gamma background from a remote source. An approach in these circumstances is to collect a swipe sample. This method has been described in Section 4.6. For relatively penetrating emissions, these wipes can be counted either directly using a standard survey monitor, or a beta swipe counter. The beta swipe counter is a typical beta detector mounted in a shielded chamber that reduces background and is connected to a scaler timer. The advantages of this process are the clearly defined swipe to detector distance, the lower background count rate of the shielded detector and the ability to count both background and wipe over defined periods which can be chosen to give adequate statistical precision.

The uncertainties in this process include the degree of self-absorption of the wipe. The major uncertainty, however, is the surface to swipe transfer factor, which is generally assumed to be 10%. This factor varies with surface, wipe material and contact pressure. The removal efficiency can be improved for many surfaces and radionuclides using swipes moistened with water, ethanol or sometimes glycerine. This tends to drive activity into the surface of the swipe. Such swipes are best counted in a liquid scintillation counter where the swipe is in direct contact with the detecting medium. This process is particularly suitable for use with low energy beta emitters, such as ^{3}H, ^{63}Ni and ^{241}Pu, but can also be beneficial for ^{14}C, particularly if the surfaces under examination are somewhat dirty. It may be necessary to prepare the samples with liquid scintillation cocktail and allow them to sit overnight before counting to allow the contamination to equilibrate with the cocktail.

One factor that is often forgotten is the contribution from conversion electrons. These are typically low energy electrons, which can be viewed as the consequence of the internal photoelectric absorption of a gamma photon. Normally difficult to detect with direct monitoring, they can contribute greatly to the count rate in liquid scintillation monitors. The system can be calibrated using a solution of known activity of the radionuclide in question to minimize the effects. However, the practicality of the situation will often demand that calibration is a combination of measurement using a limited range of easily available radionuclides followed by calculation for the radionuclides to be monitored. In this case, it is important to estimate the contribution from the conversion electrons. Otherwise, the activity present will be overestimated. A window can be set on the counter to exclude most of the counting contribution from conversion electrons.

(iii) Gamma radiation and X rays

Indirect gamma radiation and X ray monitoring have many advantages. Similar to beta monitoring, counting of swipes in a shielded chamber leads to lower background because it is possible to use thick lead shielding around the detector. Another advantage is that a multi-channel analyser coupled with a small computer can be used to identify the radionuclides present and quantitatively analyse the activity concentration of each isotope from the gamma spectrum. The lower background has the additional benefit of reducing the minimum detectable activity. Spectrometry can use either sodium iodide scintillation detectors or hyperpure germanium detectors. Sodium iodide detectors are satisfactory where the radionuclide mix is simple and the energy of interest is >100 keV, such as a mixture of ^{137}Cs, ^{134}Cs and ^{60}Co. The germanium detectors are much more expensive and complicated but offer the advantage of very good energy resolution, and better qualitative radionuclide analysis. With these detectors, activities of 1–10 Bq on a swipe can be measured for radionuclides with high probability gamma emissions with counting times of the order of 300 s.

Again, the major uncertainties are the true area wiped and the transfer fraction, which can generally introduce variability up to a factor of 10 in the determination of activity per unit area.

III.5. MONITORING TECHNIQUES FOR DIRECT MEASUREMENT OF BULK CONTAMINATION

(a) Alpha radiation

The ability to make measurements of activity concentrations of alpha radionulides without chemical pretreatment is limited by the short range of the alpha particles emitted. It is considered that the range of an alpha particle is approximately 5 mg/cm^2. A typical detector window thickness is 1 mg/cm^2, and it is reasonable to allow 1 MeV for detection, equivalent to another 1 mg/cm^2, so that alpha activity from a depth in excess of 3 mg/cm^2 will not be detected. The average response, even in this layer, will be <50% of a surface activity response. Hence, the signal from the activity concentration will be equivalent to the activity from a layer approximately 1.5 mg/cm^2 transferred to the surface. This makes normal ratemeter measurements impractical at acceptable levels. In the section on surface contamination monitoring, the minimum detectable activity for a good surface was typically 0.1 Bq/cm^2. Assuming this is equivalent to the activity in 1.5 mg/cm^2 of material, the MDA is >60 Bq/g, which is in excess of most acceptable levels for alpha emitters.

There are specific examples where at least limited success in monitoring for compliance with clearance levels is possible. The technique has some use in direct monitoring of building material, provided the limitations of particle size are understood (see Section 4.5) and, generally, provided the material to be monitored has a low, and constant, level of natural alpha background (see Section 4.3). It can be applied effectively on the surface of stripped concrete. It is not necessary for contamination to be in the form of particles but more likely has been deposited from solution.

The measurement can be performed by placing a large area thin window alpha monitor in contact with the surface, and then integrating the count for a fairly long period, such as 100 s. Either scintillation or proportional counters can be employed, provided the area is large, at least 150 cm^2, and the background is low. Monitoring for Pu and Am alpha emitting isotopes is usually acceptable but is less effective for natural U as the decay energies are much lower.

Soil is more difficult as the activity could be in the form of particles or deposited solutions or both. Soil generally has a high level of natural alpha activity which interferes with the detection of artificial or added activity as the standard could exceed the limiting acceptable level.

In some cases, the isotope of concern is a naturally occurring radionuclide and variability in background presents significant challenges. A useful property of soil is that the material is easy to process in order to concentrate the activity. The soil can be dried, weighed, pebbles removed, the material re-weighed and then reduced to a constant consistency in a ball mill. The product can then be counted in the way described, often with a silicon intrinsic detector, which has a very low background. Pebbles are removed because they have a low surface to volume ratio and, hence, are not likely to hold a significant proportion of any artificial activity. The final calculated activity per unit weight for the processed soil can then be corrected to a true dry value for the material sampled.

The spectrometric capability of the silicon detector can be used to identify the specific isotopes. Activity at the surface can deposit the complete alpha decay energy in the detector. Activity not exactly on the surface will produce a signal at less than the alpha energy. Collecting a spectrum for a very long period (typically hours) will produce a spectrum like a saw tooth. Each maximum will correspond to a particular alpha decay energy and the peaks due to acceptable natural activity eliminated from consideration; those due to other contaminants can then be assessed.

For the measurement of building material, a calibration factor can be determined using a standard large area calibration source, either ^{238}Pu or ^{241}Am, and a series of very thin absorbers, usually 1 mg/cm^2 aluminized melinex or mylar. The instrument needs to be placed on the source and the count rate, N_1, noted. An absorber is then placed over the surface and the new count rate, N_2, noted. This process is continued until the count rate is very close to background. The source used needs to be at least as big as the detector window. If it is not, it will be necessary to build up an effectively larger source by making multiple measurements. Sources with high emission rates need to be used for those measurements.

The response to distributed activity can be calculated as follows:

Surface emission = A particles·cm^{-2}·s^{-1};
Effective activity = 2A Bq/cm^2 (for 100% decay probability);

Synthesized net count rate N_{tot} from an infinitely thick sample equals:

$$\sum_{i=1}^{k} N_i = N_{tot} \tag{19}$$

where *k* is the number of readings taken;
Effective activity per unit area = 2Ak Bq/cm^2;
Effective mass per unit area = (k – 1)P mg/cm^2;
where P = mass per unit area of each absorber (typically 10^{-3} g/cm^2);

$$\text{Instrument response } \frac{N_{tot}(k-1)P}{2Ak} s^{-1}Bq^{-1}mg \tag{20}$$

This process was performed for a thin window refillable proportional counter monitor using a ^{238}Pu source. The final result for a thick source was 0.3 $g \cdot s^{-1} \cdot Bq^{-1}$. Over a period of 100 s, the background count recorded was 0, 1 or 2 counts in most cases, so a total count of 5 would be unusual. This corresponded to above background or approximately 0.13 Bq/g. The statistical uncertainty is large but it could be used as a trigger for either a longer term measurement or a more sophisticated one.

The estimated activity concentration response is then combined with the limiting activity concentration level to produce an estimated limiting acceptable count rate, noting that the alpha emitters may only represent a fraction of the total radionuclide spectrum.

Although the limit of detection is not a small fraction of the clearance level, this method has the merits of speed and low cost, which normally allow a more detailed survey than radiochemical methods. From a quality assurance perspective, the use of this method implies that an enhanced number of verification samples is warranted.

Final calibration must be performed by comparison with radiochemical analysis of the same sample and the estimated limiting count rate revised accordingly. This process has to be repeated several times before the initiation of monitoring and has to be verified regularly. If there is a variation in excess of expectations for the results from this measurement technique compared to radiochemical results, then the method can still be used as a screening process to ensure that excessively active samples are not sent for radiochemical analysis.

Calibration for soil measurements is more complicated and is generally performed by adding a known fraction of sand that has been labelled with a known activity of the radionuclide or radionuclides of interest.

(b) Beta radiation

Concerns for direct measurement of beta emitters are similar to those faced when performing activity monitoring for alpha emitters in bulk material, particularly if low energy contaminants are possible, such as ^{14}C, which emits a beta particle that has a similar range to an alpha particle. However, for high energy beta emitters, such as ^{234m}Pa, which will normally be found in equilibrium with ^{238}U, the range of several millimetres in soil makes direct in situ monitoring or sampling followed by monitoring possible at the Bq/g level.

The typical instruments used are large area scintillation detectors or proportional counters filled with a low atomic number gas. Xenon filled counters generally have too high a background count rate per unit area for use in this application.

A problem for detection of high energy beta emitters in soil is that the background could be up to fifty times the background of a similar area alpha detector. This can often be compensated for by the higher acceptable MDA because of higher exemption or clearance levels.

The monitoring technique is straightforward, when the surface in question is made flat over the area of the detector. Care should be taken to remove anything that could damage the detector window. For example, if soil is the material, it is important that twigs and roots are removed. The detector is then placed directly above the surface and the count rate integrated for a sufficient time to achieve a statistically satisfactory result. It may be to obtain a reference background. For intact (no cracks) concrete, it is possible to cut into the concrete to a defined depth, make a measurement and then cut in further. If any potential contaminant started as a surface deposit, then the concentration will decrease with depth (except, perhaps, for ^{3}H) and if the two integrated counts are statistically not different, the average is probably a good measure of background. For soil, the problem is more difficult as the diffusion gradient is usually degraded by weathering and biological agents. The reference sample is usually taken as one from an area which is quite unlikely to have been contaminated.

Given the uncertainties in this measurement technique, it is important to conduct a limited sampling programme followed by radiochemical analysis to obtain definitive results for comparison.

The calibration factor (in terms of counts $g \cdot s^{-1} \cdot Bq^{-1}$) is determined in the same way as alpha emitters, except that the absorbers will generally be thicker because of the longer range of the beta particles. For contamination from high energy beta emitters, such as ^{234m}Pa used to assess the level of ^{238}U, a suitable calibration source is $^{90}Sr/^{90}Y$, although its mix of maximum energies introduces an additional uncertainty. Aluminium sheets 0.25 mm thick are also suitable absorbers. The absorbers used in the establishment of calibration factors need to be appropriate for the expected energy of the contaminants.

This process was performed for a thin windowed refillable proportional counter with a 10 cm × 15 cm window in the beta mode for a range of radionuclides and a function derived from the response.

The result was:

$$R = 2.8\,(E - 0.1)^{1.25} \qquad (21)$$

where R = response ($g \cdot s^{-1} \cdot Bq^{-1}$) and E = maximum energy (MeV).

The value of 0.1 was subtracted to account for the effective energy threshold of the detector.

As examples for ^{14}C (Emax = 0.16 MeV), the response was 0.10 $g \cdot s^{-1} \cdot Bq^{-1}$ and for ^{36}Cl (Emax = 0.76 MeV), the response was 1.75 $g \cdot s^{-1} \cdot Bq^{-1}$. Normal background count rate is 5/s to 10/s, depending on substrate. Over 100 s, this would give 500–1000 counts, with a statistical uncertainty at the 95% confidence level of 44–63 counts. On average, a net count rate of 60 in 100 s will be noted as significant. This would correspond to an average detectable level of 4 Bq/g ^{14}C or 0.4 Bq/g ^{36}Cl.

Where there are several radionuclides present, the limiting count rate to demonstrate compliance with the established levels needs to be calculated. This process is described in detail in Section 4.3.

Care has to be taken if there are gamma emitting contaminants present. A typical mass per unit area required to form an infinite thickness for beta radiation is 2 g/cm^2, even for very high energy emitters. If the sample has an area of 150 cm^2, then the mass will be 300 g. A gamma emitter at a level of 1 Bq/g will give a total of 300 photons/s, and a count rate of about 1/s for a typical detector. This is comparable with the signal from a beta emitter at the same concentration. If gamma activity is present, it is generally more effective to monitor for the gamma emitter and then to use the radionuclide spectrum to estimate the level of beta activity. Making a comparison between beta and gamma measurements can be an effective way of checking on the consistency of the radionuclide spectrum in some circumstances.

The limit of detection is not particularly low but the method has the merit of speed and low cost, which will normally allow a more detailed survey than radiochemical methods. Final calibration has to be performed by comparison with radiochemical analysis of the same sample and this process has to be repeated several times. In the case that there are any significant variations in the results from these measurements, the method can be used as a screening process to ensure that excessively active samples are not sent for radiochemical analysis.

(c) Gamma radiation and X rays

Clearance projects frequently monitor for gamma and X rays to establish contamination activity concentrations. The level of sophistication varies. On sites where the background variation is small compared to the signal produced by activity at the clearance level, simple instrumentation can be employed, particularly if there is only likely to be one major gamma emitting contaminant. On more complex sites with significant background variations, such as an area of ground with buildings of different material, or on sites where the expected mix of gamma emitting radionuclides is variable, more sophisticated instruments such as hand held gamma spectrometers may be required. For complicated sites where the gamma mix is highly variable or where the gamma emitting radionuclide values are small because of the presence of high toxicity alpha emitters such as

^{239}Pu, then HPGe detectors are required. The strengths and limitations of each type of detector and technique are summarized in Table 14.

When clearing material as it is removed from a site, it is often convenient to monitor excavated material directly in the excavator bucket. Typically, a simple monitoring station is set up comprising a tent with one open side to give weather protection to equipment and operator and a frame into which the bucket can be placed to provide safety and also for consistency of monitoring. Monitoring point references are attached to this frame. The number of monitoring points required depends on the clearance levels adopted, the bucket size and the material self-shielding. For small buckets, which might be used for excavation of small volumes in a limited space, one detector will suffice. For larger buckets, a set of

TABLE 14. SUMMARY OF THE CHARACTERISTICS OF VARIOUS GAMMA MONITORING TECHNIQUES

Detector	Technique	Strengths	Limitations
Plastic	Hand held ratemeter.	Low cost; large areas possible.	No energy resolution.
Plastic	Box monitor.	Large detectors possible; 4π monitoring; inexpensive for area.	Limited energy resolution.
Plastic	Vehicle monitor.	Large detectors possible; weather resistant; inexpensive for area.	Limited energy resolution.
Sodium iodide	Hand held; gross.	Sensitive per unit volume; easy to move.	No energy resolution; detector needs careful mounting.
Sodium iodide	Hand held; spectrometric.	Sensitive per unit volume; easy to move.	Limited energy resolution; temperature dependent.
Sodium iodide	Installed spectrometric box monitor.	Sensitive per unit volume; available in large sizes; useful basic spectrometer.	Limited energy resolution; temperature dependent.
HPGe	Installed spectrometric box monitor.	Excellent spectral resolution.	Not available in large sizes; expensive; requires cooling.

monitoring points may be needed. Either a set of measurements are made by moving one detector from monitoring point to monitoring point or there needs to be a series of fixed detectors. Normally, two values are set. One is the average net count rate and the other is the highest individual count rate.

For some clearance projects, the most efficient arrangement may be the use of fixed instrumentation, which includes bag, box and drum monitors, conveyor belt monitors and gate monitors. These are discussed in Section III.6. of Appendix III.

Limitations and assumptions

Monitoring of bulk material for alpha and beta activity deals with radiations with a defined range. This is less the case for gamma emitters. The monitoring area and monitoring depth are normally not well defined, particularly for hand held equipment where collimators are impractical. It is possible to make some estimates of these effects but it is essential to realize that a particular count rate could be produced by a small source close by on the surface, a much larger source much further away on the surface, a uniform activity concentration activity extending for several metres and to a depth of 300 mm, or a very active layer or object buried below the surface.

A good surveyor will rapidly develop a feel for such inconsistencies and make use of the inverse square law to tell whether the count rate is caused by an object or material that is at or near the surface. The rate at which the count rate changes as the area is walked will also give clues. Buried sources will give a sharper peak in count rate as a detector is moved across them compared to surface sources.

(d) Monitoring techniques for indirect measurement of bulk contamination

(i) Collection and laboratory analysis of samples

Sampling techniques are employed where direct measurements are not possible. There are many possible reasons for this. One is that it is impossible, or at least difficult, to pick up the likely contaminants at the limiting values because of the influence of background. Another common case is where the activity concentration increases with depth. This buried activity could be revealed during gardening or building construction and give rise to unacceptable doses. A third example is that the expected contaminant emits radiation with a very short range, such as ^{63}Ni.

(ii) Sampling methods

The analytical laboratory must be involved in this part of the project. The laboratory provides helpful advice to the project management on topics such as sample size, use of preservatives, packaging and shipment, required count times, sample turnaround times, etc.

Soil

Soil is relatively easy to excavate and the aim is to remove large quantities from a site in preparation for building work or laying new services. The main problems with soil sampling in the planning stage of excavation is doing it safely and making sure the sample which is processed is unmixed and not influenced by the level of activity above or below the sampling depth. The large numbers of buried pipes, power cables and telecommunications cables that are found on a typical industrial site interfere with excavation. On older sites, many of these will not be marked on maps or, at best, will not be in the place indicated on the map. Driving core samplers any depth into the soil may be unacceptable to the site engineer. In such cases, hand digging may be the only solution.

Soil sampling can often generate samples which have been influenced by contamination from above or below the sampling depth. If a trial pit is dug by hand or machine in uncompacted soil, soil from the walls of the hole will often fall into the bottom of the hole. It is important, in such circumstances, to take samples not from the base but from the sides of the hole. If a tube-coring tool is driven into the soil, the soil next to the wall of the tool will be contaminated by activity from the layers above. If the sample is then driven out of the base of the tube, it will be contaminated by activity from the layers below. If it is driven out of the top, it will be contaminated again by activity from the layers above. To get the best from such a measurement, especially where the contaminant concentration with depth is expected to change rapidly, a coring tool that can be opened along its length, such as a split spoon, is a better choice. The core can then be removed and the outer surface removed, with a knife, which is cleaned frequently, to leave the undisturbed centre for analysis.

The same need for cleanliness and the avoidance of cross-contamination is also applied to tasks such as surface soil sampling using a trowel. The trowel needs to be cleaned between collection of each sample.

If ^{3}H is the potential contaminant, then soil samples are packaged immediately to avoid evaporation. After packaging, it could be transported quickly to the laboratory or it could be frozen, or at least kept cool, to minimize losses.

If the contamination is caused by radium, then excavation will allow much of the ^{222}Rn to escape. The majority of the gamma emitters in the radium decay chain are ^{214}Bi and ^{214}Pb, which follow ^{222}Rn. Loss of a significant proportion of the radon means that the gamma activity level will drop significantly in the following 2 h. Before gamma analysis of such samples, it is essential that the ^{214}Pb and ^{214}Bi be allowed to ingrow to reach equilibrium with the ^{226}Ra, which means that the sample would be stored in a gas tight container for a period of nominally three weeks before counting. Note that as radon is a noble gas with a relatively long half-life (3.825 d), the sealing has to be very efficient, otherwise diffusion losses, particularly for a small sample, will be unacceptable.

In theory, the same problem exists for thoron (^{220}Rn) but, since the half-life of thoron is <1 min, losses are lower and the gamma activity values recover faster.

Concrete

The surface of concrete is relatively porous and any activity which has been in contact with the surface will have leached into the surface to a degree, depending on its physical form (solid, liquid or gas) and its chemistry. Normally, the contaminant concentration will decline quickly with depth. This leads to the important consideration of what depth the sample is to be averaged over. If, for example, the concrete from an exhaust stack is to be crushed and used as fill, then it might be legitimate to average through the thickness of the chimney. If, however, the lining is to be stripped back a few centimetres and removed, then it is those few centimetres which will constitute the averaging depth. If, however, the expected values of contamination are low, it could make sense to remove only a very shallow layer for analysis. The site owner or operator can then go to the regulatory body and state that even the most potentially contaminated areas were well below regulatory concern.

Surface sample collection can use core drilling with a diamond tipped core drill, a scabbling machine, a power hammer or be done by hand using a hammer and chisel. Each method has the potential for injury to the operator and needs to be carefully controlled. Each technique has advantages and disadvantages when it comes to providing a high quality sample. Core drills can heat up the concrete close to the outer cutter and, to a lesser extent, to the centre drill, or they use water or oil as a coolant. Both reduce the local concentration of tritiated water. Scabbling machines are excellent at removing a thin, and well defined, surface layer but are noisy and also heat up the sample. Chiselling using a power hammer is noisy and gives samples of ill-defined depth and chiselling by hand is hard work and very difficult to collect a sample from high strength concrete.

It is important to select the samples carefully. Samples with potential ^3H contamination require careful handling during and after removal (see previous section on soil sampling). It is also important to note that the level of tritiated water concentration could increase with depth, reaching a maximum sometimes centimetres deep within the concrete.

Paint

Radioactivity is often trapped in paint of the material (object) monitored for release from regulatory control, and concentrations in the substrate might be less. Paint can normally be stripped easily with a scraper and collected in a plastic bag. The important point is that it will often be necessary to strip a large area in order to obtain a large enough sample for processing by the radiochemistry laboratory. This has the advantage that the sample will generally be more representative of the area than a smaller one (see Table 4).

Metals

Metals are typically impervious to most radioactive contaminants. However, ^3H can be an exception. High concentrations of ^3H as a gas, especially when under pressure or at elevated temperatures, can diffuse into metals after prolonged exposure. There are large differences in the diffusion constant and mobility between metals. If the material is relatively thin, such as a ventilation duct, then a sample can be removed with any convenient sheet metal cutter. If the sample is thick, grinding or drilling can be used with the considerations that both methods will tend to drive off ^3H contamination. Another option is repeated swabbing with a swab coated with an appropriate liquid. This can provide an approximation of the total activity in the surface of the material to be monitored for release from regulatory control.

Soft material

Soft material, such as wood, carpet and vinyl floor tiles, that needs to be monitored for compliance with established levels, can be cut easily for the purposes of sampling. Sludge from piping can also be scraped out and sealed in an appropriate container.

(iii) Analysis methods

It is important to note that almost all samples for monitoring for compliance with established levels will require some form of preparation prior to analysis.

However, methods of analysis are not discussed in detail in this Safety Report as the subject area is large. General principles and some examples are given below.

Actinides

In samples which might contain ^{239}Pu, for example, concentration of the activity is necessary, and the sample is generally dried, reduced to a fine powder, and then chemically processed. For soil, large impervious pebbles are removed first as these have a low surface to volume ratio and will generally have a much lower concentration of Pu than the finer particles. The material is sometimes ashed to drive off volatile components and then dissolved in strong acid in order to get the radioactive material of interest into solution. At each stage, the sample is weighed, so that the final measured activity can be related back to the original material which is to be considered for release from regulatory control.

The sample is processed chemically to concentrate the contaminant of interest and to remove unwanted species that might interfere with the counting process. This processing requires the addition of a tracer of the same element but different isotope, which will not conflict during the final measurement and which, itself, can be measured. The fraction of this material, which arrives in the final measurement, is termed the yield. It serves two purposes: to allow correction for losses in the real contaminant during the radiochemical procedure and also to demonstrate whether the yield is satisfactory. A lower than expected yield casts doubt on the whole analysis for monitoring of compliance with established levels.

For Pu, as an example, the output from the chemical process is then deposited as a very thin layer onto a stainless steel disc by electroplating. This disc is then placed in close contact with a very thin window large area silicon diode detector. This can be used to produce a spectrum of the alpha emissions by the source. The spectral information helps reduce the inevitable background contribution and allows the simultaneous measurement of the tracer.

The final result of measurement is the ^{239}Pu in the sample in terms of B/g. Minimum detectable activities approach mBq/g, depending on the material being analysed.

Material with very long half-lives

Material with long half-lives can be difficult to count conventionally as the mass/Bq on a final sample can be high, which can result in a sample with high self-absorption. Such material can sometimes be counted by ultra sensitive mass spectrometry that does not require the sample to decay. The initial processing of the samples of the material to be monitored for release is basically the same but the product from the chemistry stage is prepared in a form suitable for mass spectrometry.

This technique produces good minimum detectable activities for isotopes, typically with half-lives $>10^4$–10^5 a and atomic masses greater than 200, but this technique has proven useful for other radionuclides as well.

Fissionable samples

Fissionable samples can sometimes be analysed after pretreatment by placing them into a test reactor or other high neutron source. This will induce fission and leave radionuclides that can be easily detected by gamma spectrometry. Alternatively, if the sample is on a suitable substrate, then damage tracks in the substrate produced by the fission fragments can be counted.

Gross alpha and gross beta counting

Gross alpha and beta counting have been used frequently for sample measurement but have weaknesses. For soil, as an example, the procedure is to dry the soil, sieve it to remove pebbles and roots, and then to grind a sub-sample into a very fine powder. A sub-sample of the powder is then deposited as a very thin layer and placed under a thin windowed gas flow proportional counter for alpha measurement. Beta measurement can be performed at the same time using a lower energy-counting window to assess the beta activity or the sample can be placed under a counter with a slightly thicker window, which screens out the alpha particles.

The process sounds simple and attractive but it has several drawbacks. For alpha measurements, it is surprising how small a particle can be and still represent a significant attenuator. It is not appropriate where the material is present as chips or micro-spheres generated as a consequence of a machining operation or other physical process. For example, for a particle in a sphere of Pu or U that is approximately 6 µm in diameter, only 50% of the alphas escape with a detectable energy. Such a particle is not visible to the eye.

Another major problem for alpha monitoring is the calibration process. This is usually performed using labelled soil particles but it is inevitable that the size and density are different from the real sample and, hence, the measured detection efficiency is different from the real sample. Another problem is the very low mass of sample, which is normally counted. In an attempt to keep the source thin, the typical level of deposition is 1 mg/cm^2. Even with a large area counter, the sample mass will be less than 1 g and, hence, the count rate will be low at an expected clearance level.

For gross beta measurements, the same effects apply to much the same extent as for low energy beta radionuclides and to a lesser extent for higher energies. There is an additional problem with calibration in many circumstances. It is not normally possible to obtain a calibration sample labelled with the appropriate beta radionuclide spectrum and, hence, the response to the activity concentration is difficult to predict. The narrower range of alpha energies means that this problem is less severe for gross alpha counting.

The technique has some use if the contamination is expected to be in the same physical form and with the same radionuclide spectrum, but to differ in the specific activity of the contaminants. If samples are prepared and monitored using the gross alpha or beta technique and then analysed by radiochemistry, the radiochemical results can be used to provide a calibration table for the gross monitoring technique. Obviously, as clearance of material proceeds, this ratio needs to be verified at regular intervals.

Laboratory gamma spectrometry

For gamma spectrometry, the sample is usually dried to remove the effect of water content which would otherwise introduce variability between samples taken at different times. Solid samples, such as concrete, can be crushed to a coarse powder. The sample is then placed in a suitable container and placed onto the detector. Often, the container is a Marinelli beaker, a cylindrical container with a projection into its base into which the detector fits. This allows the sample to surround the detector on its circumference as well as to cover the top, gives good detection probability and reduces the average thickness of the sample for a particular volume, which helps reduce self-shielding by the sample. The detector is chosen to give adequate spectral resolution and detection efficiency for the desired MDA. The complete detector and sample are normally surrounded by shielding to reduce the background. The counting time is set, the spectrum from the sample integrated and then peaks are searched for. The energy of the peaks is then related to likely radionuclides and the areas under the peaks determined for estimation of the activity in Bq/g. For radionuclides which are not available as calibration samples, the response is normally estimated by interpolation between available radionuclides and by mathematical prediction of detector response and sample self-shielding.

III.6. MONITORING SYSTEMS

(a) Bag, box and drum monitors

In many circumstances, monitoring of certain materials for clearance is difficult until they have been removed from the premises, facilities, etc. and consolidated prior to monitoring. An example of this is electrical cable, which is difficult to monitor for surface contamination when it is in conduit or attached to cable trays. If the level of expected contamination is low and the contaminant radionuclide spectrum has a significant gamma component, then monitoring of bulk material after removal could be the best solution. This can be accomplished by using a bag or drum monitor. These are available in three basic forms, using large volume plastic scintillators, inorganic scintillators or intrinsic HPGe detectors. The size is chosen to accommodate the desired monitoring volume.

One constraint for use in monitoring material which could include hot spots is that, regardless of the detector type employed, the detector has to be able to see reasonably efficiently into the centre of the load. This obviously limits the size and density of the monitoring volume. For more homogeneous loads, such as well mixed, crushed concrete that has potentially been contaminated by liquid spills, that constraint is less limiting.

Plastic scintillator based monitors

These normally comprise a shielded box into which articles to be monitored can be placed. The box is rectangular and has six sides; typically, either four or six of these sides are made from one or more large area plastic scintillators. The box can be fitted with one door, in which case the material to be monitored enters and leaves by the same door, or it can be fitted with two doors. The advantage of the second arrangement is that the loading door can be in the contamination area and the unloading door can be in the clean area. Only if the contents satisfy the monitoring criterion will the second door unlock. If the level of activity exceeds the criterion, then the unloading door remains locked and the load has to be removed back into the contamination zone for removal of any contaminated objects.

The size of the monitor needs to be chosen for operational convenience. If values of contamination are likely to be variable, it is normally more efficient to monitor in relatively small volumes, rather than having to sort through a larger volume to identify and remove any active objects. However, if the purpose of the monitoring is basically to confirm that material meets the established levels, it could be more efficient to use a larger monitor.

Plastic scintillators have very poor gamma energy resolution and it is not possible to use spectrometric analysis to suppress the background to any great extent. This makes it important to suppress the background as much as possible using shielding, usually either steel plates or lead blocks. Normally, the shielding is removed for transport and replaced for use. Very careful alignment of the shielding is important to minimize transmission through joins and door hinges. For example, for typical shielding thickness, the transmission through intact shielding is approximately 0.01 for the normal background spectrum. If only 1% of the box is unshielded, that will double the background count rate and increase the MDA by 40%.

The size of the plastic scintillators varies. The smallest are big enough to accept a typical toolbox or plastic waste bag and their MDA is approximately 20 Bq of ^{60}Co. The largest can monitor a complete 200 L drum and may be equipped with a conveyor to move the container into and out of the monitoring volume. They can also be fitted with a weight sensor, which allows the unit to display directly in units of Bq/kg. A typical MDA is 500 Bq of ^{60}Co.

As a further refinement, some of the larger units use more than one detector per side. This enables the unit to identify the approximate position of any hot spots within the load, which simplifies their removal.

Calibration requires a number of assumptions. The radionuclide spectrum has to be stable, as the units have no spectrometric capability. Gamma emitters have to form a significant fraction of the total. The self-attenuation within the load has to be calculated and entered as part of the set-up procedure for the system. This is relatively easy for low density, low atomic number material such as paper and plastic material. It is also possible to estimate the response for contaminated material such as cabling, thin walled piping and duct work. The performance for dense loads, such as concrete and building rubble, can be calculated using routines such as Microshield or by determining the response to point sources placed in the matrix, which is more time consuming. One interesting development is the combination of a box monitor with a laser scanning process, which assesses the mass and shape of the object being monitored. This is then used to correct the reference background count and the nominal response in counts ($g \cdot s^{-1} \cdot Bq^{-1}$) to allow for the attenuation within the object being measured [20].

Inorganic scintillator based units

Inorganic scintillators, such as sodium iodide and caesium iodide, are denser and have a higher atomic number than plastic, both of which increase the overall detection probability. They also offer a higher level of spectrometric ability. Where a plastic scintillator will show a relatively featureless spectrum, with no complete energy absorption (photo peak from a photoelectric interaction) and a blurred Compton edge, a large sodium iodide detector will produce an obvious photo peak. The energy resolution is somewhat limited, on the order of 5–10% full width at half-maximum (FWHM), however, and these systems are unsuitable for applications where the radionuclide spectrum is variable and the possible emission energies are close to one another, within perhaps 50 keV. As an example, if the aim is to check for ^{137}Cs contamination in material with natural activity concentration values of U, then the 609 keV line from ^{214}Bi may interfere, to a degree, with the measurement of the ^{137}Cs 662 keV peak. Within this constraint, however, the units can be very useful. Typically, they are used where the radionuclide spectrum is relatively simple, that is, where there is a low number of relatively well spaced gamma energies. This may occur because there are few radionuclides involved in the process or because the radioactive material is old, and the majority of the contaminants have decayed, leaving only a small number of possible significant gamma emitters.

The spectrometric ability and the greater detection efficiency per unit volume also mean that the units do not require the same mass of shielding. The detector can be smaller for a defined sensitivity. In material monitoring, typical sizes range from 51 mm diameter by 51 mm depth up to several litres. Normally, the detector is surrounded by a collimator that limits the response to a defined angular range, up and down and left to right, and also reduces the background count rate. Often, the object to be monitored is mounted on a turntable, which is rotated either continuously or in steps. The detector can also often be moved vertically in steps. A combination of rotation and lift can be used to make a detailed scan of the drum or bag. Software within the unit can be used to compensate for attenuation within the load. The attenuation can be measured using an external ^{137}Cs source that is scanned over the load. The end result is a three dimensional picture of the load with hot spots and radionuclides identified.

The monitoring station can also be fitted with a shield that is on the opposite side of the load from the detector. This generally reduces the background count rate. It also reduces the influence of shielding by the load of the ambient background radiation. This shielding by the load can cause the gross count rate in a particular energy region to be lower due to the elimination of some of the background. This could result in the load being released when, in fact, the activity concentration may exceed the clearance level.

This level of sophistication means that this process is more versatile. Higher density loads can be monitored effectively and more complicated and variable radionuclide spectra used. However, the monitoring process is slower and the cost is higher.

One method of calibration is to take a clean sample of a material of interest and record the background spectrum. This effectively provides for the load shielding of ambient background radiation discussed earlier. A source of one of the radionuclides of interest is then placed at a defined place within the load and the scan repeated. The source then needs to be moved radially and to different heights within the load until activity throughout the entire volume has been modelled. The process is then repeated with a different radionuclide and then with different matrices. This process is slow and labour intensive. Another option is to consider the radiation field using a number of matrices and a number of radionuclides that are modelled using Monte Carlo methods and combined with the predicted detector response. Testing with one radionuclide, matrix and source position will then demonstrate that the performance of the unit is understood well enough for use in compliance monitoring.

Germanium detector based units

These units employ a semiconductor germanium detector. The merit of these detectors is their excellent energy resolution, typically better than 0.5% FWHM. This allows the processing of loads with variable and complicated spectra, particularly material where one radionuclide of interest, with a low clearance level, might otherwise be concealed by emissions from a radionuclide which either has a high clearance level or which is part of the natural content of the load. It can also produce lower minimum detectable activities depending on the counting efficiency. One limitation is the initial and operating cost, which is much higher than a sodium iodide scintillation detector of comparable sensitivity. Another is the fragility of the detector. In addition, there is inconsistency between detectors. A sodium iodide detector has a response that is generally consistent with size, whereas semiconductor detectors are generally more variable. Another limitation is that the detectors require to be cooled, typically with liquid nitrogen, but this can also be accomplished using an electrical cooler.

The units are normally employed as drum or bag scanners, that is the detector is collimated to relatively narrow angles and the drum is rotated and the detector moved vertically in the same way as is sometimes used for sodium iodide detectors. This makes best use of the detection characteristics. They are not available in large sizes, with the maximum size being comparable with the smaller sodium iodide detectors. This generally results in slower monitoring despite the better energy resolution and lower background.

Calibration is similar to that for inorganic scintillators. As the performance of a semiconductor detector is less predictable, another step in calibration is to determine its photo peak efficiency over a range of energies and for a range of angles of incidence. The manufacturer often does this by means of many point source measurements. Such so called ‘characterized detectors’ are increasingly being used. For such crystals, the response for any given source detector geometry can be calculated using Monte Carlo techniques, which greatly reduces time and effort.

(b) Conveyor belt monitors

Conveyor belt monitoring can be useful in a range of circumstances, particularly where the condition of a site is complicated. One of the most effective applications is to search material generated when cleaning up a radium contaminated site. Often, the majority of the activity is in the form of small but highly contaminated objects such as dials and pointers. Removing these can often result in the material being suitable for clearance [51], which in return saves disposal costs.

The conveyor belt system generally has a hopper at one end into which the material is tipped. It then feeds out at a controlled speed and a fixed depth onto the belt. The belt then passes under or between a set of radiation detectors chosen from those generally used for monitoring of bulk material. The exact choice will depend on the radionuclide mix, physical form and maximum acceptable contamination level. If the monitoring is basically for reassurance, then frequently all that is fitted to the radiation monitoring unit is an alarm and a conveyor stop switch. If the alarm sounds, the belt stops and someone searches the relevant area of the belt and removes the active object. As a higher level of sophistication, the conveyor can have a diverting mechanism fitted. Any material, which is over the limit, is diverted onto a different route and collected as active material. In both cases, the clean material generally falls off the end of the conveyor. It is also possible to fit an automated sampling device to a conveyor system. Collected samples can then be analysed in detail to confirm the radionuclides and concentrations present.

Depending on the sensitivity required, the process is not particularly fast, as the instrumentation requires time to detect the presence of a source as it passes beneath.

(c) Gate monitors

Increasingly, major clearance projects are using very sensitive monitors placed at the exit from the facility site to ensure that concentration of gamma emitting activity above certain established levels is detected and prevented from free release. One possible reason for failure is unexpected neutron activation of material which was only thought to be potentially surface contaminated. Another circumstance is where objects have not been recognized as sources, including ^{226}Ra based smoke detectors and ^{226}Ra based lightning protectors, both of which were popular 20 or 30 years ago.

A typical instrument comprises two large plastic scintillators, mounted on supports about the height of the load space on a typical truck and positioned one on each side of the vehicle route. The truck drives slowly (<6 km/h) between the detectors. The instrument detects the presence of the truck and records the count rate profile as it passes through, producing an alarm if elevated radionuclide activities are detected. These instruments are used as an added safety feature for a clearance project; they are not to be used for monitoring for compliance with exemption and clearance levels.

Appendix IV

PIPING WITH INTERNAL CONTAMINATION IN SCALE

IV.1. GENERAL ISSUE

Many industries, nuclear and other, can create internally contaminated piping (Figs 13–15). For example, oil and gas processing can lead to large quantities of piping contaminated with radium and its progeny from deposited scale on the inside of the pipe (Fig. 13). The same is true in uranium mills.

Some of the major considerations in this case include:

- Whether the piping is for reuse or disposal;
- Non-homogeneity of the activity concentration in the scale;
- Thickness of scale inside the pipe;
- Chemical and physical form of the scale;
- Whether the scale will be removed or left in the pipe;
- The possible presence of a sludge inside the pipe in addition to the scale;

FIG. 13. Oil and gas piping with scale containing ^{226}*Ra and progeny.*

FIG. 14. Piles of pipes contaminated with radioactive scale.

- Difficulties in disposal of material, both the scale itself and contaminated piping;
- Physical dimensions and condition (rust, erosion, etc.) of the piping;
- Radiation protection of workers, including contamination control during monitoring.

The primary focus of this particular example is consideration of whether to perform direct monitoring (on scale remaining in the pipe) or indirect monitoring (of the scale removed from the pipe). This example also discusses difficulties particular to equilibrium within the ^{226}Ra series, and considerations of averaging mass.

IV.2. SPECIFIC ISSUE

In this example, ^{226}Ra and, to a lesser extent, ^{228}Ra in varying equilibrium with its progeny is the primary contaminant of concern. Both of the radium isotopes have complex decay chains that include alpha radiation emitters, beta

FIG. 15. Oil and gas piping with radium scale — note the end caps used to seal the pipes.

radiation emitters and gamma radiation emitters with wide energy ranges. They also each include an isotope of radon, a noble gas, which can escape causing disequilibrium between the radium concentration and progeny concentrations. A point to consider when measuring from outside the pipe is that many of the gamma radiation emitting radionuclides are progeny of radon, and equilibrium conditions have a significant impact on the assessment. In addition, the material tends to be deposited in layers with varying activity concentrations.

This example can have two possible clearance applications. First, a decision must be made with respect to the clearance of the pipe itself. If the pipe fails, but later the contaminated scale is removed from the pipe, it could still be considered for clearance.

IV.3. REFERENCE TO REF. [2]

Radium-226 and its progeny are included in Table 1 of Ref. [2] (“Values of activity concentration for radionuclides of natural origin”). The activity concentration level for each of the radionuclides in the ^{226}Ra series is 1 Bq/g. There are nine radionuclides in the ^{226}Ra decay series, each of which must be <1 Bq/g. Two of these, ^{214}Bi and ^{214}Pb, have significant gamma radiation useful for detection and measurement.

IV.4. POSSIBLE MONITORING TECHNIQUES

Direct alpha and beta monitoring is generally not useful due to attenuation of alpha and beta radiation in the scale and through the pipe. Gamma radiation monitoring or indirect techniques are, therefore, normally employed.

Broadly, two approaches to pipe monitoring are to take:

(a) Direct gamma radiation measurements from either inside or outside the pipe;
(b) Indirect measurements of the material produced when the pipe scale is removed.

It should be noted that it might still be necessary to monitor the pipe for clearance even if the scale has been removed.

IV.5. DIRECT GAMMA RADIATION MEASUREMENTS

When considering first direct gamma radiation measurements, one of the most significant problems with measurements of radium contamination is the high dependence on the equilibrium between radium and the radon progeny. All of the significant gamma radiation emitters are radon progeny. In theory, if the equilibrium ratio between radium and its gamma radiation emitting progeny were well known, it would be a simple matter to determine the ^{226}Ra concentration from the ^{214}Bi and ^{214}Pb concentration, which is easily, obtained from gamma radiation measurements. In practice, the equilibrium ratio can vary because of the potential migration of radon from the pipe scale. As a result, there is uncertainty in the calculation of ^{226}Ra concentration based solely on gamma radiation measurements.

An advantage of direct gamma radiation measurements is that self-attenuation does not present a significant problem if the thickness of the pipe and scale are less than a few millimetres (the half-thickness of iron for ^{214}Bi 609 keV photons is approximately 3 cm). For thicker pipes, when taking external gamma radiation measurements, attenuation of the pipe wall must be taken into account. This process is more difficult for determining the radium concentration in scale because the thickness can be relatively unknown and variable.

A detector with a 50 mm × 50 mm or 75 mm × 75 mm sodium iodide crystal (NaI(Tl)) has the required sensitivity for direct gamma radiation measurements within the pipe, even if conservative equilibrium conditions are applied, assuming that clearance levels are applied to the combined mass of the pipe and scale. The NaI(Tl) detector is normally connected to a ratemeter in gross gamma mode. It should be noted that for measurements inside the pipe, using shielding for collimation if necessary, the count rate per unit specific activity is constant for a length equal to a defined number of pipe diameters, and does not depend on the pipe diameter, assuming that the contamination is uniform.

For direct gamma radiation measurements outside the pipe, the performance of the equipment is dominated by the pipe diameter and wall thickness. The thicker the pipe wall, the lower the count rate for a given level of contamination. Smaller diameter pipes provide an effectively smaller source for the same level of contamination. One advantage to measurements outside the pipe is the relative ease of using shielding for collimation if it is necessary. Collimation reduces the background and interference from adjacent sections of the pipe but reduces the detector response for contamination.

If the level of contamination of the scale alone must be addressed, the same technique can be applied if the scale thickness is at least several millimetres and is relatively uniform along the length of the pipe. Difficulties arise when the scale is very thin, of variable thickness, or if contamination values vary considerably in the scale along the length of the pipe.

IV.6. INDIRECT MEASUREMENTS

Indirect measurements involve removing scale from inside the pipe. This is normally applied when the clearance levels are applied specifically to the scale alone, when the scale thickness is non-uniform, or for scale that has been removed to reduce the contamination within the pipe to below clearance levels.

The contamination in the scale is normally measured by taking representative samples for analysis by gamma spectrometry in a laboratory. Radiochemical laboratories can have a routine procedure for this measurement. Under normal laboratory conditions, it is difficult to measure ^{226}Ra directly by gamma spectroscopy. Radium-226 only has one photo peak, at 186 keV. Not only is this photo peak relatively weak, but interference from other naturally occurring radionuclides interfere with the quantitative assessment of ^{226}Ra at concentrations on the order of the values given in Ref. [2]. Radium-226 activities are generally inferred from measurements of the gamma radiation emissions of ^{214}Pb and ^{214}Bi.

Typically, samples must be sealed and allowed to come into equilibrium prior to analysis. Depending on typical initial equilibrium ratios, a three week period between sealing the sample and performing the measurement is normally sufficient. A major source of uncertainty in this process is how well the sample(s) represent the material [51].

An issue is whether the averaging mass is acceptable to the regulatory body or other interested parties. The larger the averaging mass, the more difficult it is to ensure that the samples for analysis are representative. The smaller the averaging mass, the larger the number of samples that are required for analysis. For a larger averaging mass, one useful technique is to take a large number of samples, combine them into a single composite sample that is mixed thoroughly to ensure homogeneity, and then analyse a small number of aliquots from the composite sample. This provides an estimation of the mean concentration in the averaging mass. Analysing more than one aliquot per composite sample gives an added level of assurance that the mixing was adequate. Composite samples are appropriate if the contamination is generally uniform.

IV.7. REAL WORLD EXPERIENCE

Potentially contaminated pipes are generated in the oil and gas industry, and in phosphoric acid production. These tend to be attractive for reuse or recycling because of the high grade of steel that is often used in their manufacture.

Another issue is that of piping from uranium milling operations removed during operations and stockpiled on site, or piping from oil and gas exploration [50, 52]. These pipes have been exposed to the environment over a long period of time and are generally no longer in a condition suitable for reuse.

IV.8. SPECIFIC EXAMPLES

The following is an example of direct monitoring of scale in a pipe by taking gamma radiation measurements on the outside of the pipe.

A 100 mm internal diameter steel pipe with a density of 8 g/cm^3, 6 mm wall thickness that has 3 mm of contaminated scale with a density of 2 g/cm^3 can be considered. It should be noted that for this thickness of scale, self-attenuation will be low.

In some circumstances, averaging contamination values over the mass of both pipe and scale might not be acceptable to the regulatory body or other interested parties. In that case, the activity level of the scale within the pipe will need to be addressed specifically.

(a) Averaging over pipe and scale

In this example, it is assumed that, for this pipe diameter and scale thickness, the background count rate of an NaI(Tl) detector is 50 cps and the response of the detector is approximately 20 net cps per Bq/cm^2 of ^{226}Ra based on its equilibrium with its progeny ^{214}Bi/^{214}Pb. The contamination is to be averaged over the mass of the scale and pipe combined. To determine the net count rate corresponding to a clearance limit of 1 Bq/g, the following calculation can be done:

$$\text{CRL} = \text{S} \times [(\text{Tp} \times \text{Dp}) + (\text{Ts} \times \text{Ds})] \times \text{CV} \tag{22}$$

where CRL = instrument count rate limit, S = instrument sensitivity (net counts/s per Bq/cm^2), Tp = pipe thickness (cm), Dp = density of the pipe material (g/cm^3), Ts = scale thickness (cm), Ds = density of the scale material (g/cm^3) and CV = clearance level (Bq/g).

$$\begin{aligned}\text{CRL} = {} & 20 \text{ counts/s per Bq/cm}^2\ [(0.6 \text{ cm} \times 8 \text{ g/cm}^3) \\ & + (0.3 \text{ cm} \times 2 \text{ g/cm}^3)]\ 1 \text{ Bq/g}\end{aligned} \tag{23}$$

Thus, the count rate limit is ~100 counts/s.

In this case, the instrument net count rate would be approximately 100 cps for the total activity corresponding to 5.4 Bq/cm^2. The limit of 1 Bq/g in Ref. [2] is easily detectable using a typical NaI(Tl) detector coupled to a ratemeter.

(b) Averaging over scale only

In the next part of this example, it is assumed that the regulatory body has determined that only the scale is to be considered for the clearance of the pipe. Again, neglecting attenuation from the pipe itself, the density thickness of the scale inside the pipe is 3 mm × 2 g/cm^3 or 0.6 g/cm^2, so that the resulting net count rate is 12 cps, as shown below.

$$\text{CRL} = \text{S} \times (\text{Ts} \times \text{Ds}) \times \text{CV} \tag{24}$$

$$\text{CRL} = 20 \text{ counts/s per Bq/cm}^2\ (0.3 \text{ cm} \times 2 \text{ g/cm}^3)\ 1 \text{ Bq/g}$$

Count rate limit = 12 counts/s.

To be confident of detecting contamination at the limit of 1 Bq/g of Ref. [2], and considering the scale only (not the pipe and scale combined), a counting time on the order of 30 s per measurement will be necessary. If the net count rate is higher than 12 counts/s, the scale would fail to meet the clearance level. Should this happen, the pipe with scale could be properly disposed, or the scale could be removed from the pipe for proper disposal and the pipe then resurveyed to ensure that it meets the clearance level.

Appendix V

MONITORING OF BULK, THIN AND ABSORBENT MATERIALS

V.1. GENERAL ISSUE

This example describes the problem of monitoring thin (low g/cm²), absorbent materials.

Some of the major considerations in this case include the:

- Type and energy of the radionuclide;
- Thickness and density of the material.

This example describes some of the difficulties in monitoring thin, absorbent materials. It also discusses a monitoring solution to this problem, and some of the difficulties with this approach.

V.2. SPECIFIC ISSUE

Paper is a difficult material to monitor for activity concentration values. Paper has a typical mass per unit area of 80 g/m², equivalent to 8 mg/cm². If the limit of practical monitoring is taken as 0.1 Bq/cm², this would lead to a lower practical monitoring level of activity concentrations of 0.1 Bq in 8 mg, or 12.5 Bq/g.

$$\text{Detection limit} = 0.1\ \text{Bq/cm}^2/8\ \text{mg/cm}^2 = 0.0125\ \text{Bq/mg} = 12.5\ \text{Bq/g} \tag{25}$$

This means that any of the isotopes listed in Appendix I with limits <12.5 Bq/g could not be measured by normal surface monitoring methods.

V.3. REFERENCE TO REF. [2]

For most energetic, long half-life, gamma emitters, the Ref. [2] limit is 0.1 Bq/g.

V.4. MONITORING TECHNIQUES

A possible solution for the problem discussed in Section V.2 would be to monitor the material (paper in bags, etc.) in bulk monitors. Prior to monitoring of bulk material for radionuclides on paper, it must be ensured that the contamination is uniform and not removable, and that the material being monitored is representative.

If a significant fraction of the contamination radionuclide spectrum is gamma emitting, a bag monitor can be used to assess the bulk contamination level very efficiently. One advantage of paper is its low atomic number, which reduces the degree of self-absorption. A disadvantage is that it can form relatively dense masses. Bag monitors are effective at detecting both primary radiation and radiation which has been scattered. Hence, even if the mass per unit area between a point source and the nearest detector is considerable, scattered radiation can often reach that detector if the load is made of discrete objects with large air spaces. However, bulk paper might not be like that.

Again, restricting the mass placed in the monitor will put an upper limit on self-absorption and working at a relatively fixed mass will simplify monitoring.

Calibration can be performed easily using small sources of the appropriate radionuclide(s), placed in cut holes within a typical sample. It is important, if the paper is to be monitored in a compact mass, such as stacks of notebooks, that calibration holes are cut in the test notebooks for positioning of sources so that the notebooks remain closed. If sources are placed between the pages, there will be a clear path out through the side of the notebook and it will appear as though the detector is more efficient than it actually is.

V.5. PRACTICAL EXPERIENCE

Paper which is to be cleared can originate from offices located in controlled areas or from control rooms. In plants such as power or research reactors, where the contamination contains a large fraction of beta/gamma emitting radionuclides, direct measurements as described above are always possible. However, in plants with a high percentage of alpha contamination, other methods for clearing paper need to be used. Depending on the type of facility, a good approach is to start with wipe tests to determine whether, e.g. a suitable amount of fission products such as ^{137}Cs are present. Other radionuclides and an estimate for their contribution to the overall activity can be derived from radiochemical analysis from bulked wipe tests and from comparison with the radionuclide composition when the plant was in normal operation. In many cases, papers that were kept open for long times during plant operation, such as log books used for recording survey results and process data, were found to have significant activity contents. If a significant amount of the contamination consists of alpha emitters, simple surface contamination monitoring can fail to identify this contamination, even if there is a certain amount of ^{137}Cs present. In such cases, the use of a 4 π, well shielded bulk monitor is recommendable, and good results have been obtained with such instruments for clearance of paper in different decommissioning projects.

In order to overcome the problem, described in Section V.2 above, that surface contamination monitors would usually not be capable of demonstrating compliance with mass specific clearance levels because of the small thickness of materials such as paper, the German Radiation Protection Ordinance [12] stipulates in its Appendix III that “for a mass <3 kg in measurements ... the specific activity shall not be determined separately”, i.e. only surface specific measurements need be performed, e.g. for batches of paper (files, books, etc.). With a surface specific clearance level of 1 Bq/cm^2 for ^{60}Co and other high energy beta/gamma emitters, surface measurements of paper are possible.

V.6. LIMITATIONS

The use of bulk monitors for clearance measurements of paper or other very thin material, as outlined in Section V.4, works well for energetic gamma emitters. However, it is generally not satisfactory for ^{241}Am. This is because the gamma energy is low, leading to a reduced detection efficiency even for an unshielded source. The attenuation in most material is higher than that for ^{137}Cs and ^{60}Co; and the emission probability is low, only 36% for the 60 keV gamma, compared to 85% for ^{137}Cs and 200% for ^{60}Co.

Monitoring paper for alpha or beta contamination at typical clearance levels is difficult. Consider copying, faxing or taking digital photos of contaminated records. After converting the records into non-contaminated media, the contaminated paper can be ashed and indirect monitoring used to establish compliance with clearance levels. Another approach for handling the contaminated paper might include shredding the paper, then compressing it to achieve better homogeneity before sampling and analysing.

Appendix VI

SURFACE MONITORING OF THIN, ABSORBENT MATERIALS

VI.1. GENERAL ISSUE

This example describes the problem of monitoring thin (low g/cm^2), absorbent materials.

Some of the major considerations in this case include:

- The type and energy of the radionuclide;
- The thickness and density of the material;
- Careful consideration of the appropriate application of clearance levels (such as those in Ref. 7 [2]), taking into account the basis for the levels and the limitations of their use.

This example describes some of the difficulties in surface monitoring of thin, absorbent materials, and possible techniques to address these difficulties. Consideration is also given to a careful examination of the limitations and appropriate application of clearance levels.

VI.2. SPECIFIC ISSUE

Contaminated clothing can present a difficult monitoring problem, particularly if the radionuclides of concern emit only short-range particles. Clothing tends to be absorbent and activity can soak into the surface causing the potential for self-absorption and corresponding difficulties in detection. Clothing also has a complicated shape that makes it difficult to ensure thorough monitoring.

VI.3. REFERENCE TO REF. [2]

The values in Table 2 of Ref. [2] are ≥0.1 Bq/g. This level is easily detectable for gamma emitting radionuclides with long half-lives using bag monitors. Bag monitors can also be used to detect many of the beta emitters. However, many frequently encountered pure beta emitting radionuclides, such as ^{14}C, have a limit of 1 Bq/g, which might be difficult to measure.

VI.4. MONITORING TECHNIQUES

Clothing can be monitored by any of a number of techniques. The simplest is conventional hand monitoring, using a detector chosen to match the type of emissions from the clothing that is easiest to measure. Another method is to use a conveyor belt laundry monitor, where the clothing is moved between an array of detectors which cover both sides of the garment. This instrument requires a lightweight, open mesh conveyor. A refinement of this technique is to use position sensitive proportional counters, which will identify the position of the contaminant and have a lower effective background. Another option is to use the sorting table approach, where a table is constructed using a large array of detectors sufficient to cover one side of the garment. These instruments have been derived from the widely used whole body contamination monitor found at the exit portals at many controlled areas. When these are employed, the garment is typically monitored on one side and then turned over for monitoring on the other side. It is also possible to obtain this type of monitoring system with two sets of detectors with one set mounted in the lid.

If activity concentration values are to be applied, all of these techniques suffer from the problem that the material to be monitored is quite thin and has a low density. Typical mass per unit areas for basic protective clothing is in the low tens of mg/cm². An apparent surface activity of 0.1 Bq/cm², which corresponds to a reasonably achievable detection limit for most beta/gamma emitters, assuming no self-absorption in the material, means that the activity concentration level will be a few Bq/g, which would exceed the values provided in Ref. [2]. For low energy radionuclides, such as ^{14}C, the problem is further compounded by self-absorption within the material. In one simple experiment, using ^{14}C deposited in solution onto a laboratory coat with a waterproof backing, 3 kBq was evenly dispersed over an area of 100 cm². This was just detectable using a good quality, hand held monitor. The equivalent activity per unit area was 30 Bq/cm² and the equivalent activity per unit mass was approximately 1 kBq/g. This is 1000 times the clearance level for ^{14}C in Ref. [2].

Generally, in the absence of a significant gamma fraction, it is difficult to demonstrate compliance with Ref. [2].

One exception to this rule is where an energetic pure beta emitting radionuclide with a short half-life is used. The short half-life leads to a much higher acceptable level. As an example, ^{32}P, used in quantity in medicine and general life sciences, has a Ref. [2] level of 1000 Bq/g and a half-life of 15 d. Based on a 30 mg/cm² garment and a detection limit of 0.1 Bq/cm², the MDA will be approximately 3 Bq/g. This is only a fraction of the Ref. [2] level.

$$\text{Detection limit} = 0.1\ \text{Bq/cm}^2/30\ \text{mg/cm}^2 = 0.003\ \text{Bq/mg} = 3\ \text{Bq/g} \qquad (26)$$

Another exception is where the contaminant is an electron capture radionuclide with either a short half-life (e.g. ^{125}I, 60 d) or a very low energy (e.g. ^{55}Fe, 5.9 keV). This type of radionuclide typically has higher Ref. [2] levels. These two radionuclides have limits of 1000 Bq/g. Neither radionuclide has sufficient energy to penetrate the wall of a bag monitor effectively and both will suffer significant attenuation in bulked clothing. However, both could be detected using either a beryllium windowed thin sodium iodide detector or a thin windowed xenon filled proportional counter.

In summary, it is vital to understand the radionuclides expected to predict the response of available monitoring equipment (taking account of self-absorption) and the corresponding limits from Ref. [2]. Another solution is to use an approach based on radiological considerations and to derive specific surface contamination clearance levels for clothing from dedicated scenarios. This is a better approach than converting activity concentration values (e.g. those from Ref. [2]), which have not been derived for surface contaminated clothing, into surface specific values.

VI.5. SPECIFIC EXAMPLES

(a) Hand monitoring

Hand monitoring can be employed reasonably successfully where the contaminant is a radionuclide, which emits either an energetic beta or a low energy X ray. Alpha contamination can be detected if the contamination is not absorbed too deeply into the material, and the clothing is not wet or damp. It is also only economic where the daily number of pieces of clothing is low. Quality control is also difficult, as the process relies on the care and effort of the individual performing the task.

The following example illustrates the calculation of the surface specific detection limit from a given activity concentration value and its application. It is assumed that a laboratory uses ^{32}P and ^{125}I exclusively. The first is an energetic beta emitter and the second generates X and gamma radiation between 27 and 35 keV. Two popular types of detector cover both circumstances very effectively. One is the xenon filled, titanium windowed, proportional counter. Another is a large area, thin, sodium iodide detector. Both are capable of measuring both contaminants down to 1 Bq/cm², equivalent, in typical garments, which equates to approximately 33 Bq/g, well within the value provided in Ref. [2].

$$\text{Detection limit} = 1\ \text{Bq/cm}^2/30\ \text{mg/cm}^2 = 0.033\ \text{Bq/mg} = 33\ \text{Bq/g} \qquad (27)$$

The responses of the probe can be obtained from calibration test data. Generally, a value for ^{125}I is determined and the instrument response for ^{90}Sr + ^{90}Y beta radiation can be used to estimate the ^{32}P response.

Normally, the detector chosen needs to be guided over the garment under inspection with a gap of about 10 mm. This will allow enough distance so that buttons, etc. cannot damage the detector. The user concentrates on guiding the instrument and listens or watches for any increase in count rate. If such an increase is noted, the user moves the probe to maximize the reading and then notes the value. One complication is the use of averaging area. If a large averaging area has been adopted, then limited areas of enhanced activity will be acceptable. This requires a clear procedure for the operator to use. If the value exceeds the calculated monitoring value, then the garment has failed the test.

An alternative method for use in circumstances where a larger monitoring area is adopted is to hold the probe further from the garment, so that the effective field of view is equal or at least nearer to the permitted averaging area. An effective way to do this is to select the averaging area, cut a square hole in a table the size of the averaging area and then mount the detector beneath the hole, looking upwards on the centre line with the detector to whole distance equal to half the diagonal of the square. The garment is then placed in increments over the hole, supported on a light mesh frame, and the count integrated for some specified time, typically <1 min. At this distance, the response of the probe will be approximately 20% of that in contact with the garment. The distance from the garment needs to be limited to approximately 300 mm, since distances beyond that can create significant air attenuation.

Confirmation of the expected response is generally best performed by deliberately contaminating a known area of clothing at the limiting level. This is often possible as many laboratories use large volumes of stock solutions of known activity, which can be diluted and carefully dispensed as a series of drops onto the test area. This method makes allowance for all the variables and gives a reasonably realistic measure of the count rate at the chosen limit.

(b) Sorting table

The performance of sorting tables is similar to that of position sensitive conveyor belt monitors. There is a reduction in mechanical complexity because there is no moving conveyor belt. This is balanced against the increase in complexity of the radiation monitoring equipment, where the three detectors per side of the conveyor belt have been replaced with up to 12 detectors and their associated electronics. Calibration/instrumentation maintenance staff are usually familiar with walk-in, whole body, surface contamination monitors and, if the specific sorting table is obtained from the same supplier as the walk-in monitor, for example, very little training or spare part provision will be required.

Garments contaminated with reasonably penetrating beta emitters can be monitored in this way. Following the same logic as above, radionuclides with a limit of 10 Bq/g give a limiting activity of 0.3 Bq/cm² for typical thin clothing, assuming that the density thickness of the clothing is 30 mg/cm². Even making allowance for self-absorption, monitoring is often possible, particularly if counting times on the order of 30 s can be tolerated. A good example of this would be clothing associated with ^{131}I and ^{198}Au processing. With longer times, it is even possible to monitor for ^{90}Sr in equilibrium with ^{90}Y at 1 Bq/g.

Another relevant example is ^{90}Sr. At 1 Bq/g and typical clothing with a density thickness of 30 mg/cm², there will be 0.03 Bq/cm² of ^{90}Sr and the same of ^{90}Y.

$$\text{Detection threshold} = 1\ \text{Bq/g}\ (30\ \text{mg/cm}^2) = 0.03\ \text{Bq/cm}^2 \tag{28}$$

The ^{90}Y has a much higher energy and the ^{90}Sr will be ignored as the lower energy beta is more likely to be absorbed in the clothing. A typical sorting table detector has an area of 600 cm², which means 18 Bq of ^{90}Y will be found below each at the limit.

$$\text{Activity} = 0.03\ \text{Bq/cm}^2 \times 600\ \text{cm}^2 = 18\ \text{Bq} \tag{29}$$

With a 20% detection efficiency, this will generate approximately 4 net counts/s. A typical background for a detector of this size is 20 counts/s. Integrated for 30 s, this gives a total of 600 counts background, with a standard deviation of 24 counts or 0.8 counts/s. The alarm rate could, for example, be set at normal background + 3 standard deviations. This keeps the false alarm rate for completely clean garments down to 1 in 400 measurements per detector or about 1 in 30 for the table. The limiting response is equivalent to 5 standard deviations, which means that it is unlikely that garments contaminated above the limit will fail to be identified. However, general contamination of the garments at approximately 50% of the limit will lead to a large number of alarms. If general contamination is common on the garments, then the counting times will have to be extended to reduce the false positive rate. This could slow the processing rate down significantly.

(c) Bag monitor

The following example assumes that garments contaminated by ten year old mixed fission products derived from fuel reprocessing are to be cleared. In this case, the short half-life radionuclides will have decayed, leaving the longer half-life radionuclides such as ^{137}Cs and ^{90}Sr + ^{90}Y. It is assumed that ^{137}Cs represents 10% of the total activity and that most of the rest of the activity has a higher Ref. [2] level. Under such circumstances, an appropriate value for the acceptable gamma activity concentration could be calculated as 0.05 Bq/g. A typical bag of clothing can contain 10 kg, giving a limiting activity of 500 Bq in the bag. Even allowing for 50% self-absorption, the resultant effective activity of 250 Bq can be reliably detected in a bag monitor with a counting time of, for example, 60 s. The false alarm rates on a clean bag will be negligible at these settings.

(d) Conveyor belt based monitoring with standard detectors

This has the same measurement limitations as hand monitoring but offers the advantage that the operators only have to load and unload the conveyor, rather than make the measurements. An additional advantage is that the garment to detector spacing is controlled. The disadvantages are that the capital costs are higher, the equipment is more complicated and maintenance is more difficult. It is also not as good as really careful hand monitoring, where a skilled person will find spots of activity more effectively than the machine.

(e) Conveyor belt monitors with position sensitive detectors

Position sensitive detectors have an advantage over standard detectors in that the position of the contamination is identified. This can reduce the background at the cost of a smaller observation area, particularly for non-uniform contamination, and lead to lower detection levels. This type of monitor can be advantageous if the limits are close to the performance of standard laundry conveyor belt monitors.

Appendix VII

MONITORING OF CABLE USING DIRECT MEASUREMENTS AND SAMPLING METHODS

VII.1. GENERAL ISSUE

This example describes the problem of large volumes of surface contaminated material that will be monitored prior to recycling (e.g. copper cabling).

Some of the major considerations in this case include whether:

- Surface or activity concentration limits are most appropriate;
- Direct monitoring can be performed or sampling methods have to be applied;
- The material will be processed in some way prior to recycling (such as cutting cables and placing them into bags).

This example focuses on taking advantage of a radionuclide spectrum in direct monitoring, and the statistics of collecting representative samples for indirect monitoring.

VII.2. SPECIFIC ISSUE

Cable is an attractive material for recycling. The constituents, particularly copper, can be valuable and there are established routes in most countries for recycling. Furthermore, the contamination is located almost entirely on the insulation material, so that the cable core is free of contamination, which is an important consideration as the cables are separated into their constituents for recycling.

For potential surface contamination, it is often difficult to monitor down to the relevant values, especially if the item is being prepared for clearance. This is because the surface area of smaller diameter cable is small per unit length and, for the larger diameter cable it is difficult to hold the instrument detector close enough to monitor a significant fraction of the area of the cable. Smear samples may not provide representative measurements since some cable coverings may be braided or cloth covered, both of which tend to reduce contamination transfer onto the wipe. For potentially neutron activated cable, the outer layers can have much lower activation than the core. Alpha and beta monitoring might not be as effective as required. However, as cables are brought to recycling in nearly all cases, it is necessary to demonstrate compliance with activity concentration values such as those provided in Ref. [2].

VII.3. REFERENCE TO REF. [2]

In many circumstances associated with the nuclear industry, ^{137}Cs and ^{60}Co are likely gamma emitters and, for facilities which have been out of service for some time, ^{90}Sr + ^{90}Y often dominate the beta emitters. The corresponding levels of these radionuclides in Table 2 of Ref. [2] are 0.1, 0.1 and 1 Bq/g. For most radionuclide spectrums, the limit will be set slightly below 0.1 Bq/g total gamma because of the dominance of ^{137}Cs and ^{60}Co.

If the contamination includes radionuclides that are difficult to measure, such as ^{239}Pu, then it can be possible to develop a fingerprint and use scaling factors to derive a monitoring limit that includes all of the isotopes. For example, it can be assumed that ^{239}Pu is present along with ^{137}Cs. The levels specified in Table 2 of Ref. [2] for these radionuclides are 0.1 Bq/g and 0.1 Bq/g. If a characterization of the area generally identifies that 20% of the activity is from ^{239}Pu, then the ^{137}Cs clearance value can be modified to account for the ^{239}Pu:

$$\text{Modified level} = (0.1\ \text{Bq/g}) \times 80\% = 0.08\ \text{Bq/g} \qquad (30)$$

This relationship is true because the ^{137}Cs and ^{239}Pu clearance guides are both 0.1 Bq/g. If the ^{137}Cs value is <0.08 Bq/g during monitoring, the material is cleared for both ^{137}Cs and ^{239}Pu.

VII.4. DIRECT MONITORING

If the contamination or activation radionuclide spectrum has a significant gamma emitting fraction, then an attractive method is to use a bulk monitor. For cable, smaller units are better because they limit the degree of self-absorption that takes place in the bag to be monitored.

A characterization is performed in areas where potentially contaminated cables are located before the cabling is removed to verify that the radionuclide fingerprint is reasonably stable; then the instrument response from bag to bag remains consistent.

After the cables are removed, they could be monitored rather quickly using a sensitive hand held gamma monitor to detect elevated readings or hot spots. This is an additional precautionary step in the clearance process. The threshold level above which the reading is interpreted as a ‘hot spot’ and the cable would be rejected (e.g. for additional decontamination), has to be commensurate with averaging criteria. Cable that does not have elevated readings above such a threshold level can then be placed into a bag, drum or box for counting. Generally, it is best to fill the items to be monitored somewhat loosely in the container to limit self-absorption. For units with a built in weighing mechanism, a good practice is to fill each bundle to within 10% of a reference value that provides the basis for calibration. Frequently, local manual handling requirements limit hand loaded bags or boxes to <15–20 kg. The bundle is then placed in the monitor and counted in accordance with the manufacturer's instructions and documented procedures. The indicated activity can then be compared with the calculated limit.

It is often efficient to calculate values corresponding to segregation limits. The lower value is the instrument indication where there is a high level of confidence that the material can be cleared. A higher value instrument reading is determined that corresponds to material for which clearance levels are exceeded. Bundles giving a readout below the lower limit go to a release bin. Bundles giving a readout exceeding the higher value go into a restricted bin. Any material in between both limits can be measured a number of times in different orientations to make a more accurate assessment. Some material can be cleared and other material can be restricted. At a convenient point in the process, the bundles that had been placed in the restricted bin can be hand monitored more carefully, any hot spots that are found removed and then measured again.

During the segregation process, if a bundle has an unexpected high reading, the event is investigated in accordance with the quality management plan. This can indicate bad practice during stripping out, or cables from different areas becoming mixed, or, in the case of potential activation, the identification of areas where the neutron dose rate was higher than predicted or the cable material had changed, leading to different activation values.

The sensitivity of the bulk monitor can be checked by placing small sources of the radionuclide of interest in representative bundles in a range of positions, followed by measurement in the usual way. It is advantageous that the calibration source activities are close to the release limits. In that way, the influence of both statistical fluctuation and self-absorption can be taken into account in one set of measurements. After the measurements have been repeated several times for a range of positions and for several bundles, the instrument reading can be selected that corresponds to a high degree of confidence that each bundle would be acceptable for release.

VII.5. MONITORING USING SAMPLING METHODS

In the case where the contaminant does not include a significant gamma radiation emitting component, monitoring using sampling methods will be required. It is necessary to take a statistically relevant number of samples from a predetermined quantity of material and perform evaluation of the activity concentration values of the radionuclides that are present in the contamination. A suitable sampling strategy is based on the:

- Accuracy required for the mean values of activity concentrations;
- Mass over which the results of the clearance measurements can be averaged.

An initial number of samples per averaging mass (e.g. 10 samples/100 kg) is taken and analysed. Mean values and standard deviations for the activity concentrations of each of the radionuclides are calculated. Due to the activity variations, it is necessary to use the mean values, μ_i, plus the standard deviations, σ_i, times a suitable factor, × = 1, 2,..., for comparison with the clearance levels, Cl_i, from Ref. [2]. The index i runs over all relevant n radionuclides which are present in the mixtures of radionuclides.

$$\sum_{i=1}^{n} \frac{\left(\mu_i + x \cdot \sigma_i\right)}{CL_i} \leq 1 \qquad (31)$$

Clearance would be possible if this inequality is fulfilled.

The required initial number of samples per averaging mass and suitable criteria to determine whether this number is sufficient (e.g. on the basis of the standard variations in comparison to the mean values) need to be derived from statistical considerations which would vary depending on the measurement method, the averaging mass, considerations regarding the operating history, etc.

VII.6. PRACTICAL EXPERIENCE AND SPECIFIC EXAMPLE

A Magnox (gas–graphite) power station was being decommissioned. As part of this process, the fuel cooling pond was being stripped and decontaminated. There was a large amount of cabling, both for the general wiring associated with any industrial building and for the safety systems (gamma alarms, etc.) and the power supply to the crane. Magnox fuel ponds typically have significant levels of contamination in the water from leaking fuel, which, over a period of many years, can be transferred to the general environment. In this specific case, the pond walls had been stripped using a high pressure water jet that splashed onto the walls and cables. This caused the spread of contamination throughout the building. Prior to this event, cable monitoring may not have been required, as the general surface activity values were well controlled. However, after the event, monitoring was definitely required.

Initial monitoring was performed using a 51 mm × 51 mm NaI(Tl) scintillation detector which was passed a few millimetres from each piece of cable. Cable with readings above background was put to one side.

Heavier cable was cut into approximately 600 mm lengths. Lighter cable was coiled into loose, open coils that would fit comfortably into a standard waste bag. Each bag contained a mixture of light and heavy cable, to reduce self-absorption. The bags each contained approximately 15 kg and were placed into the bag monitor for measurement. The bag monitor had been calibrated using a small ^{137}Cs source. The results from this calibration were compared with test data from the manufacturer and found to be consistent. The lower limit of detection was approximately 100 Bq of ^{137}Cs. Using the clearance level 0.1 Bq/g from Ref. [2] and a mass of each bag of 15 kg, the activity limit was 1500 Bq, not considering self-absorption. This was equivalent to approximately 600 Bq of apparent ^{137}Cs activity when self-shielding produced by the contents was considered. This is well above the lower detection limit of the instrument.

The majority of the bags easily met the clearance levels. In those that failed, a quick search often revealed one piece with higher levels of contamination.

Appendix VIII

DIRECT MONITORING OF CRUSHED BUILDING MATERIALS

VIII.1. GENERAL ISSUE

This example describes the challenge of large volumes of material that will be monitored prior to disposal or recycling, such as crushed concrete, broken glass, soil or other building materials.

Some of the major considerations in this case include:

- Materials handling, for example, crushing, mixing and moving the large volumes of crushed material;
- Worker safety, for example, dealing with dust generated during the handling and processing of materials;
- Consideration of whether or not direct monitoring is possible (in the case where energetic gamma radiation emitters are present) or indirect monitoring will be required.

This specific example focuses on the problem of monitoring bulk material with an energetic gamma radiation emitter. The material was monitored first on a conveyor belt, and then measurements were taken on individual 1 m^3 containers.

It should be noted that maintaining a constant depth of material on the conveyor system is a difficult problem and minor depth variations can lead to misleading results.

VIII.2. SPECIFIC ISSUE

In many countries, concrete is regarded as a valuable material for recycling. In addition, the mass of building material, such as concrete or bricks, from refurbishment of a plant during operation or from dismantling certain parts of nuclear plants prior to the release of the buildings, can be quite significant. As it would be a waste of resources to treat all of this building material as radioactive waste, clearance of this rubble using, for example, the activity concentration values provided in Ref. [2] or other suitable clearance levels is a common practice. Depending on the measurement method which is used, clearance measurements can be impeded by the presence of natural radionuclides in the building material, which is to be counted as background as described in Section 4.3 of the main report.

VIII.3. REFERENCE TO REF. [2]

In many cases where building rubble is to be cleared, the contamination has a sufficient amount of gamma emitting radionuclides such as ^{60}Co or ^{137}Cs. Weak beta emitters, such as ^{3}H, which can also be present in the contamination can have a negligible or minor effect on the activity level used for clearance measurements because of their high clearance level in Ref. [2] (the clearance level for ^{60}Co and ^{137}Cs is 0.1 Bq/g, while it is 100 Bq/g for ^{3}H). The activity ratio of these weak beta emitters to the easier to detect radionuclides is determined during the characterization.

VIII.4. POSSIBLE MONITORING TECHNIQUES

Caesium-137 emits 662 keV gamma radiation that is reasonably penetrating but also easy to detect with large sodium iodide detectors. A region of interest can generally be set at this photo peak to count only the ^{137}Cs. However, in some situations, it can be advantageous to set a wider energy window, for example, if much of the radiation reaching the detector is Compton scattered and if natural levels of gamma emitters are low. In any case, it is usually worth setting an upper window when monitoring for ^{137}Cs at approximately 720 keV to reduce the contribution from natural activity in the concrete, particularly ^{40}K at 1.46 MeV.

VIII.5. PRACTICAL EXPERIENCE AND SPECIFIC EXAMPLE

The United Kingdom operated two air cooled, graphite moderated, Pu production reactors at Windscale on the north-west coast. These used air as a once-through coolant, which was then discharged up a stack. One reactor caught fire in 1957 and the other was immediately shut down. In the late 1990s, due to the condition of the two stacks, a programme was started to demolish the stack that had not been involved in the fire.

This stack was significantly contaminated because the reactor design was primitive and there had been a high level of fuel damage leading to deposition of fuel (U), as well as fission and activation products on the stack lining. The activation and fission products had diffused further into the concrete structure. During dismantling, the contaminated lining of the stack was scabbled to a depth where it appeared clean to conventional hand held radiation monitoring equipment. The remaining concrete was then checked to ensure that its activity concentration values met the site criteria for reuse.

The reactor had been shut down for 40 years and the stack flow rate reduced. The main contaminants were predicted to be ^{137}Cs and ^{3}H. This was confirmed by radiochemistry. An important observation was that the ^{137}Cs concentration decreased with depth, whereas the ^{3}H concentration increased for a few centimetres and then decreased. It was thought that ^{3}H diffused into the concrete due to the higher mobility and concentration of ^{3}H in the effluent while the stack was operating. Once operations ceased, the ^{3}H began migrating back from the concrete into the stack ventilation air.

In this case, crushed concrete from the stack was passed onto a conveyor belt under a large sodium iodide detector that was set to give an alarm at a level statistically significantly above the normal background values. The purpose of this monitor was to identify any fuel particles that could have penetrated into cracks in the concrete. The concrete was then passed into 1 m^{3} bags that were then monitored using a large volume sodium iodide detector suspended directly above the centre of the bag. Only one measurement was required because the conveyor belt monitor would have picked up a significant increase in the general level of activity as well as any hot spots. This measurement was designed to detect small increases in the general level of activity that the conveyor belt monitor would have been unable to detect because of the much smaller mass in its view and the shorter averaging time. Using this measuring arrangement and a 76 mm × 76 mm sodium iodide detector, it was possible to identify activity above 0.1 Bq/g ^{137}Cs with confidence.

The ^{3}H would only be able to be released by indirect monitoring. However, it could have been possible to determine a ratio of ^{137}Cs to ^{3}H, and apply the worst case (highest ^{3}H to ^{137}Cs ratio) to determine an effective ^{137}Cs clearance level from the formula in Section 4.7 of Ref. [2] that would be <0.1 Bq/g.

Appendix IX

PIPING WITH POTENTIAL ALPHA CONTAMINATION

IX.1. GENERAL ISSUE

This example describes the challenge of surface alpha contaminated objects with difficult to monitor surfaces.

Some of the major considerations in this case include:

- Size and shape of the objects to be monitored;
- Cleanliness and quality of the surface to be monitored;
- Whether or not the objects are good insulators;
- Whether or not every object needs to be monitored, or whether a representative sampling of the objects is sufficient to demonstrate compliance;
- Consideration of using a unique solution for an unusual and difficult problem.

This example focuses on a specific technological solution for the case of unusually shaped objects with otherwise good surfaces for alpha radiation monitoring.

IX.2. SPECIFIC ISSUE

Large quantities of piping are used in areas where there is a potential for low level alpha contamination. Easily removable internal and external contamination is monitored by swipe sampling and subsequent counting of the swipes in a low background alpha–beta counter, although the uncertainties, primarily in the sampling, are considerable as discussed in Appendix III in Section III.4. It is difficult to assess the fixed contamination on either the interior or exterior surface of the pipe.

IX.3. POSSIBLE MONITORING TECHNIQUES

For the outside of the pipe, a conventional detector will normally sit at a tangent to the pipe surface. If the pipe diameter is small, only a very narrow strip will be close enough to the probe to allow for effective monitoring. It is possible, but not easy, to manufacture scintillation detectors where the scintillator is curved and it is also possible to make segmented proportional counters which also conform to the curvature.

Another possible approach is to use the long range alpha detection (LRAD) method. The technical basis is described in Section III.3. As with all direct alpha monitoring, it only works with pipes that appear clean. Greasy or rusty pipes cannot be processed with confidence, nor can wet, painted or crushed pipes be effectively monitored by this technique. As it is not feasible to monitor the inside of the pipes easily, there must be a technical basis for ensuring that contamination is basically uniform, and that no individual elevated area above values of concern would exist.

IX.4. PRACTICAL EXPERIENCE AND SPECIFIC EXAMPLE

The following example considers clearance of pipes that could contain alpha contamination on the inside and/or the outside. This could include steel or aluminium scaffolding poles that were used for construction work in a fuel reprocessing plant where there is the potential for low level alpha contamination. If the scaffolding poles were not capped at both ends, there is also the possibility of internal contamination. Depending on the extent of the work, the number of scaffolding poles may be quite significant, so that clearance as a prerequisite for reuse at other conventional or radiological sites would be profitable. It has to be demonstrated in the clearance measurement that the total alpha surface activity is within the regulatory limit.

Appropriate clearance measurements for long pipes can be performed using the LRAD technique. The machine comprises a long duct into which the pole can be fitted. At one end of the duct, there is a HEPA filter and at the other end an ion collector and exhauster which draws the air through and around the pole. There is also a gag valve that can be closed around the outside of the pipe, so that the airflow is purely through the pipe. By making a measurement of the current generated with the flow both over and through the pipe, and with it through the pipe only, the contamination inside and outside the pipe can be measured. If contamination were detected inside the pipe, the pole could be turned round. If the current increases slightly, the contamination is at the end now closer to the ion collector. If it decreases slightly, it is then at the far end.

Used in an area of low gamma background, the instrument had a threshold of detection of approximately 20 Bq. Pipes can be processed at a rate of one every 5 min. The same approach can be used for ducting and for smaller diameter pipes. For smaller pipes, the current generated per average alpha decay is less and a different calibration factor is required. This can be determined by using a small area alpha source inserted into the pipe.

A variation of the technique can be used for complicated objects such as valve bodies. As long as air flows over every surface, then significant alpha activity will cause an increase in the current from the ion collector when the airflow is over the active area. The instrument, in this case, has a turntable onto which the object is placed. The output from the ion collector is plotted and will change as the turntable rotates. The machine can be set to record the peak current. It will even detect alpha activity down blind holes, provided they are no more than approximately 50 mm deep and are at least 15 mm wide.

IX.5. LIMITATIONS

The LRAD monitor only works for the detection of alpha radiation and other radiation with high specific ionization. The limitations of the technique are that good insulators must not be placed in the measurement chamber since these can have high surface charges that can collect in the air stream. The limit of detection is influenced by the radon and moisture concentrations in the ambient air. The performance of the ionization chamber can be affected by any source of ionization, including smoke, static electricity, potential RF sources, infrared, etc. High beta–gamma or neutron background can affect the ionization chamber.

Appendix X

OBJECTS WITH SURFACE BETA CONTAMINATION

X.1. GENERAL ISSUE

This example describes the problem of monitoring objects with surface beta contamination for reuse or recycling.

Some of the major considerations in this case include:

- The cleanliness and quality of the surface;
- Accessibility of the surface;
- Type of material (e.g. steel, wood);
- The energy of the beta radiation.

This example focuses on the challenges of monitoring beta contamination on a difficult to access surface with a thin coating.

X.2. SPECIFIC ISSUE

Beta monitoring may be required on a variety of surfaces. Some surface types are relatively easy to measure. Others, including surfaces from process piping, laboratory glassware, reagent bottles, air sampler pumps and many other materials are more difficult to measure because of geometrical interference. Beta activity on the surface of other materials can be shielded by a surface layer that is difficult to remove.

A large chemical engineering building was being demolished. Much of the floor of this building was made from 10 mm thick steel plate. Uranium-238 was used in a series of experiments in the early days of the building causing some surface contamination. Later in the life of the building, the steel plate had been covered with industrial grade linoleum. There was approximately 100 t of the floor plate; the objective was to find a way to demonstrate that the contamination level was acceptable for recycling.

X.3. POSSIBLE MONITORING TECHNIQUES

The specific isotope that is causing the potential contamination determines, to a large extent, the monitoring technique that will be most useful and cost effective. Many beta emitting radionuclides either emit gamma radiation directly or their immediate progeny do so. If this is the case, conventional gamma monitoring techniques such as the use of a bag monitor may be appropriate.

If the potential contaminant is either a pure beta emitter or only emits low energy or low probability gamma radiation, the problem becomes more difficult. For materials that have a thin coating and are potentially contaminated by a high energy beta emitter, it is sometimes possible to monitor through the surface coating. For some objects, it can be possible to find, or design and make, a detector to fit inside the object. For some objects, the only viable solution is to cut the object open to make its internal surfaces available for direct monitoring. Even then, the shape can impose limitations on the size of the detector that can be employed.

X.4. REFERENCE TO REF. [2]

The mass per unit area of the plate was 8 g/cm^2. The Ref. [2] limit for ^{238}U is 1 Bq/g. Given that compliance would be ensured by demonstrating that the active layer was <8 Bq/cm^2, assuming that the contamination was distributed throughout and the regulatory body concurred. Project release levels were 50% of this level.

X.5. PRACTICAL EXPERIENCE

The first step was to remove the linoleum. Most of the thickness pulled away easily, but a thin backing layer approximately 2 mm thick with a density of about one remained. Uranium-238 is an alpha emitter with an immediate progeny of ^{234m}Pa that emits beta particles with a maximum energy of 2.27 MeV. It seemed possible that a sufficient fraction of the beta particles emitted would penetrate the backing and could be detected.

It was desirable to use standard radiation protection instrumentation. The equipment selected was a 100 cm^2 thin windowed beta scintillation detector. This was connected to a digital ratemeter with an energy variable, width counting window. A standard anodized ^{238}U contamination monitor calibration source traceable to national standards was used to set up the instrument and derive a response. The source was then covered with paper to the same mass per unit area as the linoleum backing. The ratemeter and detector window width of the counting channel were optimized to reduce the background in order to improve the detection limit of the contaminant. Reducing the ratio of upper to lower window ratio from its standard value of 15 to a value of 5 reduced the background to <2 counts/s without greatly reducing the response to the source. This gave reliable detection for ^{234m}Pa using a 10 s counting interval. The probe was not held stationary during the count but was scanned over the selected averaging area of 1000 cm^2. Using this technique, it was possible to clear about 10 m^2 (or 1 t) of plate per hour. The result was a dramatic saving in disposal cost.

Appendix XI

MONITORING OBJECTS WITH BETA CONTAMINATION PENETRATED INTO A SURFACE

XI.1. GENERAL ISSUE

This example describes the challenge of monitoring objects for beta contamination that has penetrated into the surface. This case was selected because of the difficulty caused by attenuation of beta particles from contamination below the surface.

Some of the major considerations in this case include the:

- Depth profile of the contamination;
- Type of material (e.g. steel, wood);
- Energy of the beta radiation.

This example focuses on the challenges of monitoring brickwork for a relatively low energy beta emitter that has penetrated several millimetres into the surface. In addition, the importance of verification of results is discussed (in this case, by the use of multiple independent laboratories for sample analysis).

XI.2. SPECIFIC PROBLEM

A building had been used over many years for work with uranium hexafluoride processing. For a period, reprocessed uranium containing significant quantities of ^{99}Tc, a relatively low energy (294 keV Emax) beta emitter, had been used. There had been some leaks during this period and the brickwork was contaminated in a small number of areas. The building was now excess and to be prepared for transfer; the objective was to demonstrate to the regulator that the ^{99}Tc activity was below clearance levels.

XI.3. REFERENCE TO REF. [2]

The level for ^{99}Tc in Ref. [2] is 1 Bq/g.

XI.4. POSSIBLE MONITORING TECHNIQUES

The ^{99}Tc was suspected of having diffused an unknown distance into the brick. As ^{99}Tc is a low energy beta emitter, any direct measurement will be superficial only. Inspection of the decay scheme showed that there were no useful

X or gamma emissions nor any energetic progeny. The best approach seemed to be to optimize a detector to measure the surface activity and gain knowledge of the depth of penetration into the brickwork through the removal of successive layers with subsequent monitoring. Complicating the measurement were generally measurable values of uranium contamination.

XI.5. PRACTICAL EXPERIENCE AND SPECIFIC EXAMPLE

A scintillation based, 100 cm^2 beta contamination detector with a standard thin window was chosen to conduct the measurements because of its low maintenance requirements and its low gamma response to the uranium progeny. The detector operating voltage and counting window were optimized to provide the lowest surface activity detection for ^{99}Tc. Larger area detectors were available but not considered for use because they did not perform as well at measuring low energy beta radiation and they were more difficult to use when making measurements on walls.

After the monitoring instrument was operational, it was necessary to identify areas of elevated contamination, record the instrument indication, and then carefully scabble 1 mm deep layers from the surface. The dust from each layer and each area selected was collected in clean vacuum bags attached to the scabbling machine. A total of six layers were removed. Each sample was then split into three volumes and sent to each of three radiochemistry laboratories to provide a quality check for the organization’s radiochemistry laboratory compared with two other nationally recognized laboratories.

When the analyses were returned, the results from the three laboratories were compared. The agreement between the company’s laboratory and what was regarded as the national leader was excellent. The comparison with the other laboratory was weaker but there was no systematic shift, only a higher fluctuation in the ratio either side of unity. As a result of this test, the company’s laboratory was considered adequate for this project.

The results were plotted against depth, normalized to the surface result, and a very clear and consistent trend identified. Within a reasonable uncertainty (30%), each layer was a fixed fraction of the previous layer, and not greatly dependent on sample location. The results were combined to give a normalized concentration versus depth ratio for the areas considered. The laboratories also provided analytical data for uranium for each sample. The depth profile from these analyses followed the same general pattern as the ^{99}Tc but with a shallower slope, i.e. the concentration dropped more slowly with increasing depth. The results for both radionuclides fitted an equation of the form:

$$C_{d+1} = K \times C_d \tag{32}$$

where C_{d+1} = concentration in the subsequent layer in Bq/g, C_d = concentration for layer d (Bq/g) and K = constant derived from the ratio of the concentrations.

The concentration of ^{99}Tc was below the limit of detection for the fifth and sixth layers whereas uranium was still just above the limit of detection.

The concentration for the surface layer of the brick, C_s in Bq/g, was then converted to surface activity in Bq/cm^2 (according to Eq. (2)) as the thickness of each layer of brick removed was 1 mm, and the density of the material was 2.3 g/cm^3.

$$\begin{aligned} A_s\ (\text{Bq/cm}^2) &= C_s\ (\text{Bq/g}) \times 2.3\ \text{g/cm}^3 \times 1\ \text{mm} \\ &= C_s\ (\text{Bq/g}) \times 0.23\ (\text{g/cm}^2) \end{aligned} \tag{33}$$

where A_s = activity of the surface layer in Bq/cm^2.

The subsequent layers were then summed to get the total activity per square centimetre of brickwork. The sum to infinity was used as the concentrations fell rapidly with depth in the brick. Total activity in each square centimetre of brick through the thickness of the stack was determined as the surface activity in Bq/cm^2 divided by the quantity (1 – K) (as $(1 + K + K^2 + K^3 + \ldots)$ equals $(1 - K)^{-1}$). The standard function is then:

$$A_{tot} = 0.23\ A_s/(1 - K) \tag{34}$$

where A_{tot} = the activity of each square centimetre through the thickness of the stack in Bq/cm^2 and A_s = the activity of the surface layer of the stack in Bq/cm^2.

The total activity was then divided by the mass of the 100 mm thick, 1 cm^2, column of brick, i.e. 23 g in this case. The final result was thus:

$$C_{avg} = \frac{A_{tot}}{m_{tot}} [0.23\ A_s/(1 - K)]/23 = A_s/[100\ (1 - K)] \tag{35}$$

where C_{avg} = the average activity concentration through the thickness of the stack (100 mm).

In this manner, the surface activity in Bq/cm^2 could be related to the average activity concentration through the thickness of the stack. In the example considered, for ^{99}Tc, K = 0.6, which calculates to the average concentration in the brick equating to the surface concentration divided by 40. The same process was undertaken for uranium.

The wall of the building was a cavity wall with two layers of brick, the outer of which was effectively clean. The regulator allowed the use of the average of the outside and inside layers in the calculation of activity concentration.

The instrument responses were then calculated in terms of cps per Bq/g. Fortunately, there were areas of relatively high ^{99}Tc/U surface contamination and vice versa which assisted in the choice of response factors. The limiting count rates were then calculated for both radionuclides for the selected radionuclide and the lower one of the two chosen as the operating limit.

Appendix XII

MONITORING OBJECTS FOR SURFACE CONTAMINATION

XII.1. GENERAL ISSUE

This example describes the challenge of monitoring objects with various types of surface contamination for reuse or recycling. This could include furniture, transport containers, etc.

Some of the major considerations in this case include the:

- Emissions (type and energy) of the radionuclides that might be present;
- Cleanliness and quality of the surface.

This example focuses on the importance of understanding what type of radionuclides can be present (e.g. through gathering material history and process knowledge) in order to select the appropriate monitoring instruments and techniques.

XII.2. SPECIFIC PROBLEM

Laboratory furniture is frequently moved from area to area. Laboratory management can release benches and other furniture from an area where unsealed radioactive material has been used to an uncontrolled area. As part of this process, it is important to be confident that the level of accessible surface activity is low and that levels of activity which could be made accessible by, for example, stripping off surface varnish or polish are also low. This is not a trivial problem as records of radionuclides and activity concentrations of sources used in each laboratory are not always reliable, particularly for very old furniture. It is often wise to assume that the surfaces may have been contaminated with a wide range of radionuclides and that longer half-life radionuclides may still be present in significant quantities.

It is essential to remove melamine-faced boards that have been used to cover bench surfaces since they are sufficiently thick to attenuate even energetic beta radiation.

Some laboratories are old enough to have been used for radium work before the early 1950s when standards were not as conservative as current requirements and it was a common practice to paint over contamination to fix it in place.

As sealed source records are not reliable, a careful survey of drawers, closets and other areas need to be performed using a sensitive gamma scintillation detector as the primary tool to detect gamma sources which have fallen behind panels or, in some cases, behind furniture.

XII.3. REFERENCE TO REF. [2]

Radionuclides such as ^{226}Ra have clearance levels of 1 Bq/g [2]. Other radionuclides commonly used in university research, such as ^{125}I, have levels of 100 Bq/g. Longer lived radionuclides used in laboratory research include, for example, ^{14}C, whose clearance level is 1 Bq/g.

XII.4. POSSIBLE MONITORING TECHNIQUES

The laboratory has to be monitored using a sodium iodide scintillation detector with crystal dimensions of at least 19 mm depth × 25 mm diameter. Areas that need to be emphasized in the survey include behind radiators, the backs of cupboards, drawers and sink traps.

If no sources are detected, then a wide energy range, large area, beta scintillation detector is used to monitor surfaces such as bench tops. A unit with a smaller detector is used to monitor edges and the under side of bench tops, water taps, gas taps, electrical power points and light switches. Detection limits of approximately 1 Bq/cm^2 are possible if the equipment is used carefully.

Although this type of detector will also respond to alpha activity, it cannot detect the typical alpha clearance levels because of the significant background. An option is to use a dual probe that responds concurrently to alpha and beta radiation. Good examples of these include gas filled proportional and dual phosphor scintillation detectors. These types of detectors have a wide beta energy response and effective alpha and beta discrimination. A conventional alpha probe can be used if the combination detector is not available. Detection limits of approximately 0.1 Bq/cm^2 are possible if the equipment is used carefully.

If no elevated levels are detected, monitoring using a sensitive low energy X ray detector with a beryllium or aluminium entrance window is performed. It is important to monitor benches and other furniture that have been used for alpha work, including storage of unencapsulated material. This type of instrument will detect radionuclides such as ^{55}Fe but will also detect contamination by transuranics, such as ^{241}Am and ^{239}Pu, that have been varnished over. The limit of detection is higher, typically 4–20 Bq/cm^2 depending on the decay probabilities. An area that displays an enhanced X ray count rate is stripped to the bare wood. Paint or polish that is removed can be analysed to identify the contamination. The bare wood surface is then surveyed.

XII.5. PRACTICAL EXAMPLE

A pharmaceutical company was selling a small suite of laboratories to another company that planned to perform similar work. The furniture and fittings were to be retained. Records indicated that the main radionuclides used were ^{125}I and ^{32}P, but there were suggestions that ^{55}Fe and ^{14}C had also been used. The surfaces were in good condition and had not been painted or covered and there was no indication that alpha emitters had been used. The surfaces had been cleaned regularly, reducing the probability that removable activity in appreciable quantities was present.

The laboratory was surveyed carefully with a 100 cm^2, wide energy range beta probe and a 30 mm diameter thin window sodium iodide detector with a low energy threshold of <5 keV. Three areas of contamination were found. One was on the edge of the sink where the bench surface had been damaged, another was a small area inside a fume hood and the third, the highest, was the wooden back of the nail brush in the hand washing area.

Appendix XIII

MONITORING ODDLY SHAPED OBJECTS FOR SURFACE CONTAMINATION

XIII.1. GENERAL ISSUE

This example describes the challenge of monitoring surface contaminated objects, which are difficult to monitor as a result of their shape.

Some of the major considerations in this case include:

- The emissions (type and energy) of the radionuclides that might be present;
- The cleanliness and quality of the surface;
- Whether the contamination is fixed or removable;
- Additional attention to verification due to large uncertainties as a result of the difficult surfaces.

This example focuses on the distinction between fixed and removable surface contamination, and challenges in reliably measuring removable contamination.

XIII.2. SPECIFIC ISSUE

Nickel-63 is used as the ionization source in gas analysers. A low energy (Emax = 66 keV) beta emitter, ^{63}Ni, has a half-life of 100 years. The energy is such that it is detectable with a low efficiency on a good surface. In this example, the surfaces are stainless steel, which implies that direct monitoring is possible. The aim of the project is to demonstrate that equipment from the area can be removed to an uncontrolled part of the building for unrestricted use.

Before monitoring, any normally accessible areas of the facility where there is the possibility of surface coatings concealing activity are cleaned to the original surface. If this is impractical, the material is treated as low level radioactive waste. Equipment that seems difficult to monitor by reasons of its shape (narrow tubes, deep slots, etc.) are also consigned as waste or aggressively cleaned and disposed of as non-radioactive waste after inspection confirms removal of the surface layer.

XIII.3. REFERENCE TO REF. [2]

The clearance level for ^{63}Ni from Ref. [2] is 100 Bq/g. For this example, the regulatory body has agreed on the use of a surface contamination limit of 100 Bq/cm^2.

XIII.4. POSSIBLE MONITORING TECHNIQUES

The low energy beta radiation can be detected directly with low efficiency. For a typical thin windowed scintillation detector or proportional counter, the detection efficiency, defined as the count rate per unit emission from the surface directly below the detector and in virtual contact with the detector, is as low as 2%, less than one twentieth of the efficiency for higher energy beta particles. This definition requires that the surface is clean, since slight layers of grease, dirt, moisture or oil will significantly attenuate the radiation.

An alternative approach is to take swipes of the surface for analysis by liquid scintillation. The advantage to this approach is that the result will be less dependent on surface condition but imposes additional uncertainty because of the non-quantitative transfer coefficient, typically considered to be 10%. This approach also requires a high level of care on the part of the person taking the swipe to ensure a representative sample of the correct dimensions is collected.

XIII.5. PRACTICAL EXAMPLE

In this case, both methods are employed to demonstrate compliance. The bench tops and suitable equipment are surveyed with a 100 cm^2 thin window beta scintillation detector with the high voltage set just below the point where the background began to climb excessively and an upper threshold set just above the point where there was no more change in the count rate from an electrodeposited ^{63}Ni calibration source. This maximizes the response to the contaminant while minimizing the background count rate. The instrument, equipped with easily removable 1 mm thick feet to allow the instrument to be placed directly on large flat surfaces, was used in the ratemeter mode. The response was established using a proprietary calibration source, with an activity of approximately 1 $s^{-1}\cdot Bq^{-1}\cdot cm^2$. The word ‘approximately’ is used because of the important calibration source considerations indicated by ISO-7503-1 [34] and described in NUREG-1507 [22]. The energy and angular distribution of the emissions on a calibration source are not the same as that of a perfect material deposited on a surface. The instrument is also operating at the low energy end of its capability. The instrument performance is typically a background of 2 counts/s and an expected count rate of about 100/s at the limit of 100 Bq/cm^2.

The instrument is moved over the flat bench tops and flat surfaces of equipment virtually in contact. Any area where the count rate exceeds 10/s, approximately 10% of the limit agreed with the regulatory body, is marked. After marked areas are decontaminated, swipes are taken and counted by liquid scintillation monitoring, and the area monitored again with the instrument. The total removed activity can be determined by summing the activity on the swipes and comparing with the average instrument derived apparent activity over the area wiped. The ratio of the activity in the first swipe to the total activity removed can be used to provide a better estimate of the transfer coefficient.

If this procedure provides reasonably consistent results over the first several areas of contamination encountered, then further areas can be processed purely on the basis of the established instrument response. However, the ratio of instrument indication to removable activity may be variable. In that case, an option is to set the acceptable count rate limit below the value that has been found to correspond to the lowest effective instrument response, provided that the value has some statistical validity. Another option, particularly if the transfer coefficient seems reasonably consistent, is to use the level above to trigger swipes with the final disposition decision based on the results of the swipe samples.

Equipment with complicated shapes, where it is impossible to obtain a good instrument measurement, will be surveyed by swipe samples only. Transfer coefficients for corners and cavities are difficult to assess and most users will rely on the standard 10% or on the derived transfer coefficient from the process described above.

In summary, both direct measurements with appropriately calibrated instruments and swipe samples are necessary to provide adequate monitoring to demonstrate that ^{63}Ni contamination on clean surfaces of materials and equipment meet release levels.

Appendix XIV

MONITORING OF SOIL CONTAMINATED WITH A GAMMA EMITTER

XIV.1. GENERAL ISSUE

This example describes the challenge of monitoring soil or other bulk materials containing gamma radiation emitters.

Some of the major considerations in this case include:

- The acceptable averaging volumes or masses;
- Complications arising from the distribution of contaminants (e.g. whether they are found throughout the material or present in discrete particles, whether there is a radon transport issue, and whether a natural process such as groundwater flow, erosion, etc. has affected the distribution of radionuclides);
- The problem of background (often variable) from naturally occurring radionuclides.

This example focuses on how to compare field measurements with values derived from the Ref. [2] levels. It should be noted that soils left on a site are not within the scope of Ref. [2] as they are considered part of the site, whereas soils being removed from a site, and monitored to demonstrate compliance with clearance levels, are within the scope.

XIV.2. SPECIFIC ISSUE

A former smelting plant produced many tonnes of slag containing enhanced concentrations of thorium. This slag was subsequently mixed with many thousands of tonnes of soil and spread across a small industrial property.

XIV.3. REFERENCE TO REF. [2]

Thorium-232 and its ten radioactive progeny are naturally occurring, and therefore the Ref. [2] level is 1 Bq/g each.

XIV.4. POSSIBLE MONITORING TECHNIQUES

Several of the thorium series radionuclides (e.g. ^{228}Ac) are good gamma emitters. Unlike ^{226}Ra and its progeny, the thorium series does not have the complication of a long lived noble gas within the series. Although ^{220}Rn is a noble gas, its half-life is only 56 s and, therefore, does not normally diffuse very far in soil. As a result, gamma radiation measurements of thorium contaminated soil can be related to the thorium concentration in the soil. Direct monitoring by gamma radiation measurements on the outside of packages, etc. is the method of choice for this situation. In some cases, gamma spectroscopy can be utilized effectively.

XIV.5. PRACTICAL EXAMPLE

In this case, the regulatory body agreed to an averaging volume equivalent to one truckload (Figs 16 and 17) with some assurance that the material was relatively homogeneous. This assurance was based on knowledge about:

- The distribution of thorium in the slag material;
- The slag material itself;
- Initial measurements of thorium in the soil and of dose rates across the industrial site;
- The mixing method used;
- Activities at the site since the disposal of the slag material.

The primary investigations also ruled out the possibility that small quantities of soil could have a concentration of activity much higher than the clearance level. The specific monitoring method employed was to take time-integrated gamma radiation measurements outside of each individual truck (only one type of truck was used) to ensure a well defined counting geometry. Each load was made in the same way, i.e. with the same amount of material placed in the same configuration. The truck was taken to a measuring station situated some distance away from the site in order to reduce the background contribution. At the measuring station, the truck weight was recorded and the truck was placed in a well defined position relative to several detectors. The detectors were placed along the sides of the truck and above the load. The detectors were collimated and ‘looked’ into almost the same amounts of soil. The contribution from background was obtained from counting a truck loaded with non-contaminated sand in the measuring station. All of the detectors had a dose rate background in the interval 0.02–0.03 μSv/h. The conversion factors from net dose rates to the mass specific content of thorium homogeneously distributed in the soil were obtained from measurements on a load of soil with well known activity content from the site. This calibration load had been mixed thoroughly and the activity concentration obtained by analysing multiple samples from the load in a calibrated laboratory counter.

The calibration measurement net responses were approximately 0.4 μSv/h per Bq (thorium)/g for each of the detectors, which was verified by radiation transport calculations. By repeating measurements (including unloading and loading the same soil from the truck several times) the total measurement uncertainties were determined, although individual uncertainties, for example, the density of soil which can vary, could not be determined empirically. It was shown that dose rate measurements obtained from 1 min measurements result in an MDC of homogeneously distributed thorium of 0.1 Bq/g. At levels close to 1 Bq/g, the content could be determined with an uncertainty of 10%. One minute was chosen as the standard measuring time.

It was agreed with the regulatory body that a truckload of soil would be processed in the following manner:

(a) The weight of the soil on the truck is measured and must be within a 15% interval of the weight of the soil load that was used for calibration in order to be measured.
(b) If the weight is within tolerance, the truck is counted for 1 min.
(c) The measured dose rates from the detectors are converted by the conversion factors to activity contents of ^{232}Th. The mean of these calculated activity concentrations, C_{mean}, are taken to be the activity concentration of ^{232}Th in the truckload.

If $C_{mean} < 0.7$ Bq/g, the soil can be cleared. The limiting activity is below the Ref. [2] level of 1 Bg/g in order to account for the uncertainty in the determination of the average activity concentration.

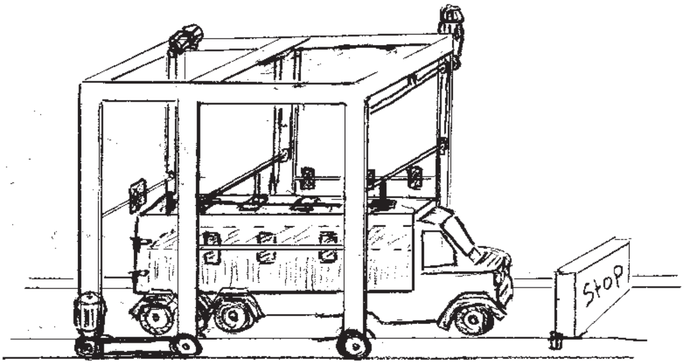

FIG. 16. Schematic drawing of the measuring station.

FIG. 17. Practical example of the measuring station.

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