The UK Nuclear Industry Guide To:

Clearance and Radiological Sentencing: Principles, Process and Practices

This Nuclear Industry Guide was produced by the Clearance and Exemptions Working Group and published on behalf of the Nuclear Industry Safety Directors Forum (SDF)

May 2017

Revision History

Issue Number	Revision Date	Changes
Interim Issue	May 2003	Incorporating comments from consultation Jan - March 2003
Issue 1	Jun 2005	
Issue 1.01	Aug 2006	Update of Secretary's details.
Issue 1.03	Aug 2011	Amendments to Section 3.1 to reflect update of Transport Regulations.
Issue 2	Dec 2012	Rewritten to reflect revised legislation relating to clearance and exemption of wastes and materials.
Issue2.01	May 2017	References to Nuclear Industry Code of Practice replaced with Good Practice Guide.

It is recognised that – through the experience of using these Guides – there may be comments, questions and suggestions regarding its contents.

In the first instance, any such comments should be sent to the following

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1   Foreword

This Good Practice Guide details the principles, processes and practices that should be used when determining whether an article or material may be released from any further controls on the basis of radiological protection considerations.   It identifies approaches to segregate radioactive or potentially radioactive substances and articles from non-radioactive (or 'out of scope') substances and articles.

Historically substances or articles consigned from a nuclear licensed site as being 'clean' have been termed 'free release' but, because the management of such releases are subject to stringent controls, they are better termed controlled clearances

In addition to substances or articles which are out of scope (i.e. are not radioactive for the purposes of regulation under the Clearance and Exemption legislation), the exemptions provisions documents permit certain substances or articles which are, or may be, identified as radioactive, to be consigned as 'exempt' from further regulation based on their radiological properties (subject to compliance with specified conditions, notably relating to management practices).   Whilst this category is likely to be a minor consideration for many nuclear licensed site operators, it is included within this Good Practice Guide to assist compliance with the clearance and exemption regulations

All such clearances do, of course, have to meet the requirements of relevant legislation and, ultimately, it is compliance with relevant legislation, rather than this Good Practice Guide, that would be tested.   However, it is intended that if the methods described in this document are properly applied and the criteria met, then relevant legislation will be satisfied, and the article or substance in question can be released for disposal or re-use without further control

Notwithstanding the contents of this Good Practice Guide and adoption thereof, individual organisations may, on the basis of corporate risk considerations, decide that articles and substances which are not radioactive in law should still be treated as radioactive, or potentially radioactive, and reused or disposed accordingly

This Good Practice Guide is not, in itself, a working level procedures document.   It is aimed at those responsible for formulating organisational policy and developing working level guidance

This Good Practice Guide cannot practicably identify every type of controlled clearance that takes place, although every effort has been made to cater for all generically applicable situations.   It is inevitable that specific situations will arise which are not completely covered by the processes and practices given.   Where such situations do arise, users are asked either to refer them for determination and agreement of good practice, or communicate the means used to address the situation, to the Clearance and Exemption Working Group at the address on the previous page

Finally, this issue represents the nuclear industry understanding of the most robust way of undertaking controlled clearance at the current time. We recognise, however, that the approach to, and view of, any activity in life is in a constant state of change and this area is no different

1.1   Safety Directors Forum

In a sector where safety, security and the protection of the environment is, and must always be the number one priority, the Safety Directors' Forum (SDF) plays a crucial role in bringing together senior level nuclear executives to:

- Promote learning;
- Agree strategy on key issues facing the industry;
- Provide a network within the industry (including with government and regulators) and external to the industry;
- Provide an industry input to new developments in the industry; and,
- To ensure that the industry stays on its path of continual improvement.

It also looks to identify key strategic challenges facing the industry in the fields of environment, health, safety, quality safeguards and security (EHSQ&S) and resolve them, often through working with the UK regulators and DECC, both of whom SDF meets twice yearly. The SDF members represent every part of the fuel cycle from fuel manufacture, through generation to reprocessing and waste treatment, including research, design, new build, decommissioning and care and maintenance. The Forum also has members who represent the Ministry of Defence nuclear operations, as well as "smaller licensees" such as universities and pharmaceutical companies. With over 25 members from every site licence company in the UK, every MoD authorised site and organisations which are planning to become site licensees the SDF represents a vast pool of knowledge and experience, which has made it a key consultee for Government and regulators on new legislation and regulation.

The Forum has a strong focus on improvement across the industry. It has in place a number of subject-specific sub-groups looking in detail at issues such as radiological protection, human performance, learning from experience and the implementation of the new regulatory framework for security (NORMS). Such sub groups have developed a number of Good Practice Guides which have been adopted by the industry.

1.2   Sub-Group Description

This document is produced by the Clearance and Exemptions Working Group, which is a sub-group of the Safety Directors' Forum. The Working Group brings together a wide range of representatives of nuclear operators, from all the Licensees across the United Kingdom, including:

- Civil, commercial and defence activities;
- Design, operation and decommissioning of nuclear facilities;
- Research facilities.

The purpose of the Working Group is to provide guidance that is useful to, and will benefit the widest possible range of UK nuclear operators.

Such guidance is not mandatory, nor does it seek to identify minimum standards. It aims to provide a tool kit of methods and processes that nuclear operators can use if appropriate to their sites and facilities.

These guides are intended to improve the standardisation of approach to the delivery of a clearance regime.

When using the information contained within these guides, the role of the Intelligent Customer shall always remain with the individual nuclear operator, which shall retain responsibility for justifying the arguments in their respective Clearance Regimes. The Environment Agency and Scottish Environment Protection Agency are consultative member of the Clearance and Exemption Working Group.

The following companies and organisations are participating members of the Clearance and Exemptions Working Group:

1.3   Disclaimer

This UK Nuclear Industry Guide has been prepared on behalf of the Safety Directors Forum by a Technical Working Group. Statements and technical information contained in this Guide are believed to be accurate at the time of writing. However, it may not be accurate, complete, up to date or applicable to the circumstances of any particular case. This Guide is not a standard, specification or regulation, nor a Code of Practice and should not be read as such. We shall not be liable for any direct, indirect, special, punitive or consequential damages or loss whether in statute, contract, negligence or otherwise, arising out of or in connection with the use of information within this UK Nuclear Industry Guide.

This Guide is produced by the Nuclear Industry. It is not prescriptive but offers guidance and in some cases a toolbox of methods and techniques that can be used to demonstrate compliance with regulatory requirements and approaches.

Definitions

ALARP	As Low As Reasonably Practicable. In this Document, where public doses are addressed, *ALARA* (As Low As Reasonably Achievable) is implied by the use of *ALARP*.
Article	Something solid which has been manufactured; everything is either an *article* or a *substance*. Following practice in other relevant regulations (including the Transport Regulations, the terms *object* and *item* are also used in this document and have the same meaning as *article*.
Assessment	Use of all existing information about the nature, *history* of, and *measurements* associated with, an *article* or *substance* to permit further decisions to be made (including *sentencing* decisions).
BAT	In broad terms, "Best Available Techniques" means the latest stage of development of processes, facilities or methods of operation which is practicable and suitable to limit waste arisings and disposals. Identification and implementation of BAT implies a balanced judgement of the benefit derived from a measure and the cost or effort of its introduction.
Bulk material or bulk waste	A significant quantity of a *substance* or mixture of *substances* which has some degree of uniformity and usually originates from a common source.
Clean	An *article or substance* that has never been contaminated or activated. This is usually declared on the basis of *provenance* (although supporting or reassurance *monitoring* may also be undertaken without introducing any implied belief that the article or substance may be contaminated or activated).
Clearance	The entirety of the process to confirm that an *article* or *substance* is *out of scope* or *conditionally exempt*.
Compliance volume	In some instances, because of *measurement* limitations, a number of similar *sentencing volumes* may be cleared as *out of scope* or *conditionally exempt*, but the confidence level is not as high as required. Under such circumstances it is acceptable practice to bulk such sentencing volumes, following sentencing, to produce a larger compliance volume that permits the overall confidence level to be met. It is important to note that this is not dilution as it is undertaken after *sentencing*.
Conditionally Exempt	An *article* or *substance* that is radioactive or contaminated under the *Exemptions Provisions Documents,* because it contains levels of specified radionuclides above out of scope limits; but is conditionally exempted from further regulation based on its radioactive properties because it contains levels of specific radionuclides or radioelements as appropriate below the exemption limits under the exemption provisions documents. The term *Conditionally Exempt* is used throughout this Good Practice Guide to emphasise that conditions are attached to *articles* or *substances* exempted from further regulation under the *Exemption Provisions Documents* based on its radioactive properties.

Definitions

Contamination	Radioactive substances on surfaces, or within solids, liquids or gases, where their presence is unintended; or the process giving rise to their presence in such places. The term contamination refers only to the presence of radioactivity not to the scale of the hazard. Surface contamination may be *fixed* or *non-fixed*.
Disposal	Emplacement of waste in an appropriate facility without the intention of retrieval.
Environmental Regulators	The Environment Agency is the primary environmental regulator in England and Wales with responsibility for permitting disposals of radioactive waste. The Environment Agency is constituted as an executive non-departmental Public Body responsible to the Secretary of State for Environment, Food and Rural Affairs and a Welsh Government Sponsored Body responsible to the Minister for Environment and Sustainable Development. The Scottish Environment Protection Agency (SEPA) is Scotland's environmental regulator. SEPA is constituted as a non-departmental public body, accountable through Scottish Ministers to the Scottish Parliament.
Excluded	A term used previously to describe an *article* or *substance* that is not radioactive under the Radioactive Substances Act 1993 and not subject to any control under the Act. The current regulations do not distinguish between *clean* or *articles* or *substances* which are otherwise *out of scope*. In this document the term excluded is used to identify an article or substance which cannot be declared *clean* on the basis of provenance but which may still be declared *out of scope* if suitable measurements confirm the absence of activity above *out of scope* limits after normal background has been taken into account.
Exempt	See *Conditionally Exempt*.
Exemptions Provisions Documents	New provisions to replace the previous exemption order suite were introduced in England and Wales by the Environmental Permitting Regulations 2010 as amended by the Environmental Permitting (England and Wales) (Amendment) Regulations 2011. The Radioactive Substances Exemption (Scotland) Order 2011 likewise introduced material previously covered in the suite of exemption orders applicable in Scotland. To simplify reference to the two new sets of legal exemption provisions these statutory instruments are referred to in this document as the *exemptions provisions documents*.
Fingerprint	A radionuclide *fingerprint* is an estimate of the anticipated radionuclide mix of an *article* or *substance*, and is often referred to when producing an activity assessment during the characterisation of radioactive material. Fingerprints are used to infer and quantify the presence of other nuclides by measuring one, or a limited number, only.
Fixed and Non-fixed contamination	For the purposes of the transport regulations, *non-fixed contamination* can be removed from a surface during routine conditions of transport. For all other purposes, *non-fixed contamination* is taken to be any surface contamination that can be removed taking reasonable measures (e.g. *wiping*). *Fixed contamination* is any contamination other than *non-fixed*.
History	See provenance.
Item	See *article*.

Definitions

Justify	To possess or provide adequate evidence to support an action or conclusion.
Legislation	Legislation refers to all relevant legal requirements and regulations. The term is generally introduced here to differentiate between legal requirements (which must be complied with) and explanatory guidance (which typically interpret or amplify the requirement and indicate how compliance may be demonstrated).
Limit of Detection	This term has been in use for many years to describe the lowest level of activity (whether expressed as total activity or activity concentration) at which a sample or measurement would be identified as not background, for a defined probability. See also *maximum missable activity*.
Material	A material is a *substance* or *article* that is not waste.
Maximum missable activity	The activity or activity concentration at which a sample or measurement would be identified as not differentiated from background, for a defined probability.
Measurement	The processes of *monitoring* and/or *sampling* (including *wiping*) as appropriate to the circumstances and including the results obtained.
Monitoring	A direct *measurement* procedure for detecting radioactivity using an instrument which detects radiation.
Normal background	The appropriate background level of radioactivity in an *article* or *substance* to be taken into account during *clearance* and *sentencing* according to circumstances.
Object	See *article*.
Out of Scope	An *article* or *substance* that is not radioactive under the *Exemptions Provisions Documents*. Other regulations may apply.
Premises	In general, within the *Exemption Provisions Documents* the word 'premises' can be taken to mean any building or group of buildings etc. within a bounded area where, if an environmental permit were required, one permit would apply. Premises may include any land, whether covered by buildings or not, including any place underground and any land covered by water.
Provenance	A knowledge of the use (including location) and controls which have been applied to an *article* or *substance* to determine its potential to have become activated and/or contaminated by radioactivity, and the nature of any potential activation or contamination (sometimes termed *history*).
Quality plan	A plan which specifies the activities and sequence of activities to be carried out, the procedures and instructions to be used, the inspection activities, the hold points, and the decision criteria, and identifies relevant individual responsibilities and record keeping requirements.
Radioactive article or substance	In this document, this is an *article or substance* which is not *out of scope* or *conditionally exempt*.
Reasonably practicable	A proven or achievable action or standard of operation for which it may be reasoned that the overall cost of implementation, in terms of time, trouble or money, is not grossly disproportionate to the actual or expected benefit.
Relevant liquid	The *exemption provisions documents* define a *relevant liquid* as a non-aqueous liquid, and certain types of aqueous liquid with specified hazardous properties. The purpose of this definition is to allow such liquids to be treated, for the purposes of clearance and exemption, as a solid because the exposure pathways are the same as those for solids.

Sampling	An indirect *measurement* procedure which includes taking a sample for preparation and assay/counting in another location.
Sentence/Sentencing	That step of the *clearance* process at which the decision is made that an *article* or *substance* is *out of scope, exempt* or *radioactive*.
Sentencing volume	The volume of an *article* or *substance* over which an individual *sentencing* decision is taken.
Smearing	See wiping.
Substance	A liquid, gas or solid that is not an *article*. It may or may not be *waste*.
Substantially insoluble solid	A solid (including suspensions of particulates) where the solubility is sufficiently small that the disposal impact is dominated by the solid form, rather than from any *material* that may dissolve and escape. NB: this is a working definition; legal definition would be strictly a matter for the courts.
Sum of Quotients	Where reference is made to an article or substance possessing an activity concentration or quantity of radioactivity which does not exceed the relevant value in the *Exemption Provisions Document* as *Out of Scope* or *Conditionally Exempt*, that value is not exceeded where: (a) only one radionuclide which is listed or described in the relevant table is present in the material or waste and the concentration or quantity of that radionuclide does not exceed the concentration or quantity specified in the appropriate entry of that column in that table; or (b) more than one radionuclide which is listed or described in the relevant table is present and the sum of the quotient values of all such radionuclides in the material or waste is less than or equal to one. For materials containing a mixture of radionuclides in fixed proportions, the limit on specific activity is calculated as the inverse of the sum of each radionuclide's activity divided by the proscribed limit for the particular radionuclide. Effectively: $$100 / \left(\Sigma_1^n X_i/Y_i \right)$$ Where X is the specific activity of each radionuclide in the mixture; and, Y is the corresponding exclusion limit.
Surface contaminated item	An impervious *article* or *item* (or exceptionally a *substance*) with accessible surfaces, which has the potential to be contaminated by radioactivity only on or at its surfaces, and has not been activated. Such radioactivity must be detectable by external measurements (*monitoring* and/or *wiping*). (NB: A *surface contaminated item* is not necessarily the same as a surface contaminated object (SCO) under the Transport Regulations.
Swabbing	See wiping.
Waste	An *article or*, *substance* which is identified as having no further direct use. Wastes may be consigned for disposal or for recycling.
Wiping	A procedure which is intended to remove a sample of surface radioactivity, if present, by wiping (or *swabbing or smearing*), in order to estimate the level of loose surface contamination present. The wiping procedure may use a wet wipe or dry wipe, and the wipe is processed and assessed in another location, usually by *monitoring*.

Executive Summary

For clarity, it is necessary to define certain characteristics in order to present an unambiguous procedure for clearance and radiological sentencing. Throughout this document, everything is considered to be either an article (i.e. a manufactured solid) or a substance (i.e. everything other than an article). This defines the physical property. In the same way, everything is either a waste (i.e. a substance or article which has no further use) or a material (i.e. any substance or article which is not a waste). This defines the potential use or purpose.

The current exemption provisions documents provide for clearance and sentencing of a wide range of articles and substances under specified conditions. At the broadest level, three categories are defined within the new regime.

- Waste and material outside of the scope of regulation ('out of scope'). Effectively, out of scope equates to 'not radioactive' for the purposes of the Clearance and Exemption legislation. Radioactive substances which are out of scope are not subject to any regulatory requirement under this legislation (but do remain subject to any other relevant legislation, for example based on non-radioactive properties).

- Waste and materials conditionally exempted from the requirement for a permit under the legislation ('exempt from permitting'). Conditionally exempt articles and substances are radioactive (i.e. they are not out of scope) but are exempt from the need for a permit under EPR/RSA. They remain subject to any other relevant legislation, for example based on non-radioactive properties.

- Waste and materials subject to an environmental permit.

This defines the radiological properties for the purposes of the exemption provisions through tabulations of radionuclide specific values of activity or activity concentration.

The Government has published guidance on the scope of exemptions from the radioactive substances regulations*. Paragraph 1.21 and Tables 2.2 and 2.3 of that Guidance identify radionuclide specific activity concentrations that, for the purposes of the clearance and exemption legislation "are not deemed to be radioactive" (i.e. they are out of scope). Similar radionuclide specific total activities on any premises, and activity concentrations of materials and wastes, that may be conditionally exempt from permitting are presented in Tables 3.1 and 3.4 of the Guidance.

The basis on which the various numerical values and waste disposal criteria have been developed is mainly related to the radiation dose which could be received by a member of the public, although there are exceptions to this general concept.

This Good Practice Guide summarises the rationale underpinning the exemptions regime and sets out the principles, processes and practices to demonstrate compliance with the provisions of the exemptions regulations. Interactions with other legislation (e.g. the Transport Regulations, the Ionising Radiations Regulations and the Environmental Protection Act) are explored in Chapter 2.

This Good Practice Guide is not applicable to:

- the transfer of articles or substances from one area to another area within a single site or premises, where this is achieved by management control and containment during transfer.

- the delicensing of land on nuclear licensed sites.

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* Guidance on the scope of and exemptions from the radioactive substances legislation in the UK. Guidance Document, September 2011, Version 1.0, www.defra.gov.uk.

Living people and animals are not subject to control under the exemptions provisions documents, although personal risk considerations and IRR 99 require them to be monitored and decontaminated where possible.

The Concepts of Clean and Excluded

A number of key concepts are introduced in Chapter 3 of this Good Practice Guide. This includes the definition of 'clean' materials and wastes.

The majority of articles or substances used on a nuclear site will not be contaminated or activated during use and, in radiological terms, will be the same as similar articles or substances used in any work environment. It is therefore unsustainable and unreasonable to treat such articles or substances as radioactive, because this would unnecessarily prevent their re-use or recycling or would require an inappropriate use of disposal facilities for radioactive materials.

For the purposes of this Good Practice Guide, two sub-categories for articles or substances which are out of scope are introduced, as follows:

- *Clean* - the provenance of the article or substance is sufficient to justify a belief that there has been no potential for activation or contamination.

- *Excluded* - the article or substance has been used in areas where there is potential to become contaminated or activated (or where previously identified activation or contamination has occurred); however, monitoring or measurement confirms that the article or substance is below out of scope limits (or previously identified radioactivity has been removed to levels below the out of scope limits by radioactive decay or decontamination).

Given an *a priori* belief that an article or substance lies in one or other of the two cases above, the only difference lies in the level of monitoring required to confirm that the article or substance in question is out of scope. *Excluded* articles or substances will always require monitoring prior to classification. *Clean* articles or substances do not require monitoring, although reassurance monitoring may be undertaken on a discretionary basis. Note that in the latter case monitoring does not imply a belief that the article or substance is radioactive, but may be used simply to confirm a belief that it is clean.

It is acceptable practice to physically separate and segregate articles or substances so that each constituent can be treated appropriately. For example, painted steel can be segregated into the paint layer and the steel itself.

Other concepts and practices not specified by regulations or regulatory guidance considered in Chapter 3 of this Good Practice Guide address issues of dilution of wastes and materials, homogeneity of properties (e.g. activation or contamination), confidence levels for sentencing, the introduction of sentencing or compliance volumes and the clearance of surface contaminated items or materials.

Management Principles

The aim of government policy for the management of materials and wastes is to achieve sustainable development. In response to this aim, the following objectives are identified.

- to avoid where possible, and otherwise minimise, the creation of radioactive items and materials;

- to avoid where possible, and otherwise minimise, the creation of all wastes, including clean and conditionally exempt wastes, and to maximise the quantities of potentially radioactive items and materials that may be correctly cleared as out of scope or conditionally exempt;

- to maximise re-use and recycle options and minimise the need for disposals;

- to achieve a high level of safety in all disposals;

- to have a high level of confidence that sentencing is technically correct and is demonstrably safe; and,

- to undertake these activities in compliance with all relevant legislation (governing both radiological and non-radiological properties).

In addition, permits or authorisations for discharges, disposals and transfers granted by the environmental regulators (EA and SEPA) always contain a mandatory requirement to apply best available techniques (BAT), for permits issued under EPR in England and Wales, or the equivalent best practicable means (BPM), for authorisations issued under RSA in Scotland, to the management and minimisation of waste. For simplicity, other than direct references to the relevant regulations, only BAT is referred to in this document, but the term is always used to be inclusive of BPM.

A number of principles are advanced in Chapter 4 of this Good Practice Guide, with respect to safety and environment, plant operation and QA arrangements, to ensure that the objectives underpinning BAT are met.
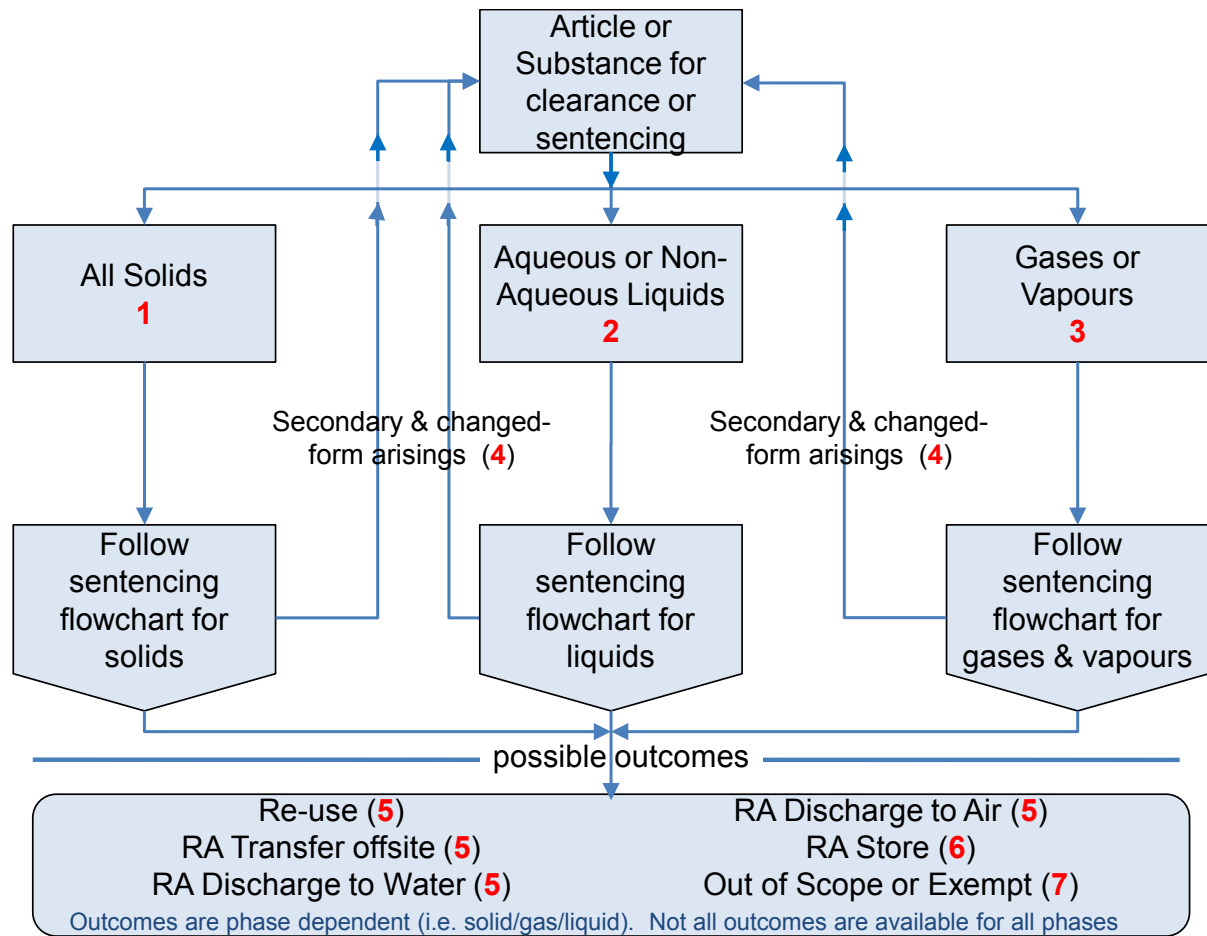
Clearance and Sentencing Processes

Chapter 5 of this Good Practice Guide sets out an overview of the clearance and sentencing routes for all types of potentially radioactive articles or substances (solids, liquids and gases). It identifies the sentencing routes to be followed, including any secondary arisings or changed form arisings which could be produced from any treatment or process, and the range of possible outcomes which can result.

Sentencing of solids is much more complex than sentencing of relevant liquids or gases because of the variety of types of solids, the greater potential for solids to conceal radioactivity (including both small and large particles), the greater potential to contain a high degree of non-uniformity, the larger number of options for monitoring and sampling, and the greater complexity of, and potential for, treatment. Sentencing of solids therefore follows a number of possible routes. In addition, clearance and sentencing arrangements are reviewed to ensure that all sentencing and clearances comply with relevant limits under the exemptions provisions.

Specific guidance is offered for solid items or materials, surface contaminated items or materials, liquids, gases, vapours and activated or tritiated materials or items.

Executive Summary

Overview of Clearance and Sentencing Routes for Potentially Radioactive Articles and Substances

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                          ┌─────────────────┐
                          │  Article or     │
                          │  Substance for  │
                          │  clearance or   │
                          │  sentencing     │
                          └─────────────────┘
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All Solids **1**	Aqueous or Non-Aqueous Liquids **2**	Gases or Vapours **3**

Secondary & changed-form arisings (**4**)   Secondary & changed-form arisings (**4**)

Follow sentencing flowchart for solids	Follow sentencing flowchart for liquids	Follow sentencing flowchart for gases & vapours

──── possible outcomes ────

Re-use (**5**)   RA Discharge to Air (**5**)
RA Transfer offsite (**5**)   RA Store (**6**)
RA Discharge to Water (**5**)   Out of Scope or Exempt (**7**)

Outcomes are phase dependent (i.e. solid/gas/liquid). Not all outcomes are available for all phases

1. Including surface contaminated articles and high surface area to volume articles (such as clothing).
2. Including sludges and suspended solids.
3. Including aerosols and particulates.
4. Secondary arisings may be in the same or different form due to physical and chemical treatment.
5. Transfer or discharge is subject to appropriate permitting.
6. If no disposal route is available, storage may be the only option.
7. Both out of scope and conditionally exempt materials or wastes remain subject to legislation relevant to non-radioactive properties.

Monitoring, Sampling and the Statistical Basis for Sentencing Items and Materials

Sampling strategy in support of a sustainable approach to radioactive waste management in the nuclear industry is based on:

- generation of a sampling plan that will provide demonstrable compliance with the regulatory requirements for clearance of materials; and,

- ensuring that the sampling and assessment process is robust and defensible.

Chapter 6 of this Good Practice Guide establishes the basis for measurement practices, including the principles of monitoring, monitoring equipment, sample preparation and measurement approaches, and development of an overall plan. These areas are then explored in more detail in the following chapters. Approaches to monitoring and sampling strategy are considered in Chapter 7 and Chapter 8 considers radiochemical analysis of samples.

The major volumes of wastes or materials generated on nuclear sites contain a mixture of radionuclides, which contribute to the total activity. The ease with which these different

radionuclides may be detected and quantified depends upon the type of radiation they emit, the energy of their radiation, the potential for absorption of radiation within the waste or material itself, their abundance and a host of environmental and practical considerations.

It is common practice within the nuclear industry to establish approximate ratios of radionuclides within the waste or material in order to facilitate later assessment of the activity within discrete items or materials. A comprehensive list of the radionuclides that are likely to be present in the waste or material, and their relative contributions to the total activity, is commonly known as a fingerprint.

Fingerprints are used to infer the activities of difficult-to-measure radionuclides, based on limited information about the contamination present within a particular waste, material or item. Provided it is valid to establish and use fingerprints in support of overall activity assessments, their application tends to simplify the process of characterising wastes or materials. Chapter 9 of this Good Practice Guide introduces approaches to establishing robust fingerprints.

The intended purpose of the fingerprint should be carefully considered at the outset in order to determine the range of radionuclides and the level of accuracy with which they require to be reported. In any case, without exception, when preparing any fingerprint it is necessary to review the operational history of the wastes or materials, noting possible contamination mechanisms, the nature of radioactivity that might therefore be present and the location of this activity. Where fingerprints are applied to infer the activities of a limited set of all remaining radionuclides in the waste or material, these radionuclides must be clearly defined within the scope of the fingerprint and all other types of activity must be measured using other means.

The statistical approach to sentencing requires that a numerical level of confidence in the sentencing decision is defined, and the sampling data are compared against this level of confidence in order to determine whether the material being sampled is above or below the action limit. Chapter 10 explores the statistical basis for sentencing, based on sampling and analytical procedures.

A number of appendices are also presented, clarifying and expanding on specific themes or providing examples of approaches that may be adopted. Determining background levels, tests, the concept of maximum missable activity and monitoring and measurement techniques are presented in Appendices A, B and C respectively. Statistical approaches to analysing data and identifying confidence levels for decision-making are considered in Appendix D. Worked examples for the derivation of an out of scope activity concentration for a radionuclide not specified in the Government Guidance and the derivation of surface clearance values are presented in Appendices E and F.

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Appendices

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Tables and Figures

2   Introduction

2.1   Aim of this Good Practice Guide

1.1   This Good Practice Guide summarises the rationale underpinning the current clearance and exemptions regime and sets out the principles, processes and practices to demonstrate compliance with the provisions of the clearance and exemptions regulations.

1.2   This document is presented in three component parts (Figure 1.1): an Executive Summary, the Main Report and separate Appendices providing information too detailed to go into the main report.

Figure 1.1   Document structure
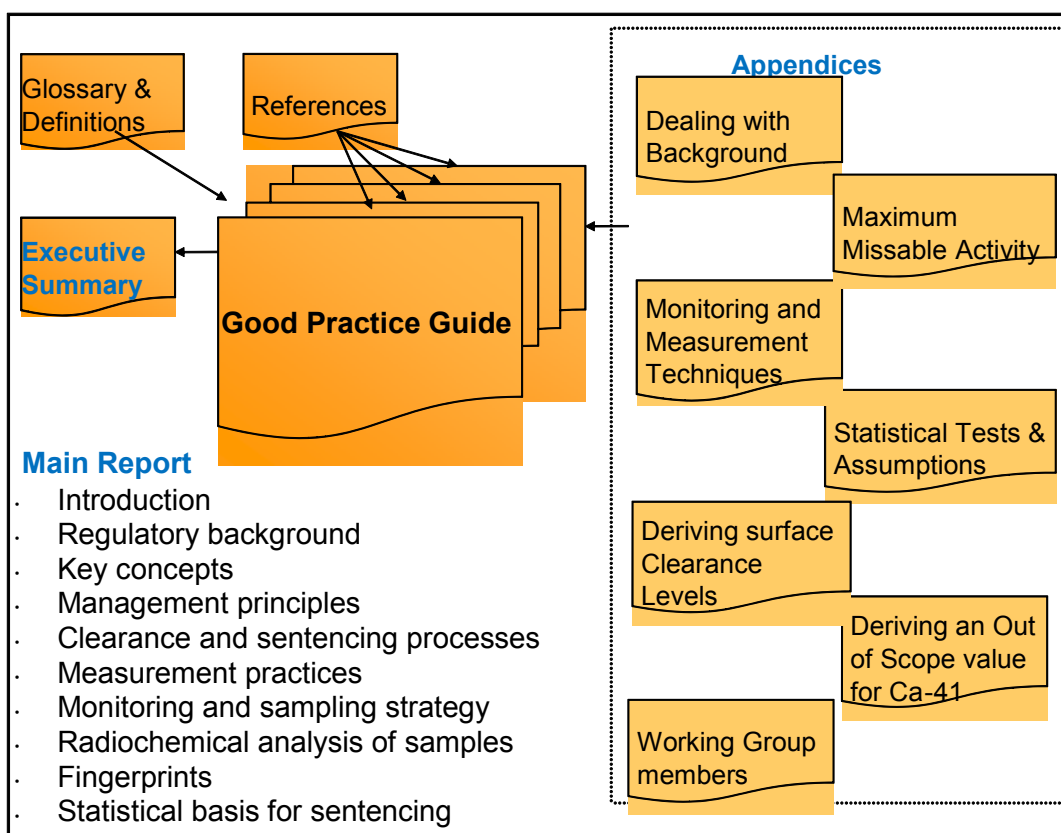
1.3   Each main Section is intended to be self-contained and is supported by external references as appropriate.   Internal cross-references are minimised between Sections but cannot be avoided altogether.

2.2   Scope and Application of this Good Practice Guide

1.4   This Good Practice Guide is aimed primarily at the nuclear industry and is intended to provide strategic and policy guidance for those responsible for formulating organisational policy and developing working level procedures applicable to operators of nuclear licensed sites. The Good Practice Guide draws on examples of good practice within the nuclear industry.

1.5   Although this Good Practice Guide is intended to be 'stand-alone' there are circumstances where the clearance and exemption legislation needs to be

consulted for a strict legal interpretation. In the case of any doubt, reference should be made to the legislation itself and the associated Government Guidance [1].

2.3   What This Good Practice Guide Does Not Cover

1.6   This Good Practice Guide is not intended to be used for the transfer of articles or substances from one area to another on the same premises where this is achieved by management control and containment during transfer.

1.7   This Good Practice Guide is not applicable to the delicensing of land on nuclear licensed sites or the surrender of an authorisation/permit. Delicensing of land within the boundary of a nuclear licensed site is subject to regulation by the ONR under the Nuclear Installations Act 1965 (NIA 65) [2]. In order to delicense the whole or part of a nuclear licensed site, the licensee will be required to demonstrate that the criteria for 'no danger' have been met [3].

1.8   Living people and animals are not subject to control under the exemptions provisions documents, although personal risk considerations and IRR 99 [4] require them to be monitored and decontaminated where appropriate.

2.4   References

1   Guidance on the scope of and exemptions from the radioactive substances legislation in the UK. V 1.0 Sept 2011. Llywodraeth Cymru, DoENI, Scottish Government, DECC, DEFRA. http://www.defra.gov.uk/publications/files/pb13624-rsl-guidance-110914.pdf

2   Nuclear Installations Act 1965 (amended). Available from http://www.legislation.gov.uk/ukpga/1965/57

3   Health and Safety Executive (2005) Criterion for Delicensing Nuclear Sites. Available from: http://www.hse.gov.uk/nuclear/delicensing.pdf

4   The Ionising Radiations Regulations 1999. Statutory Instrument 1999 No. 3232. The Stationery Office. Available from: http://www.legislation.gov.uk/uksi/1999/3232/contents/made

3   Regulatory Background

3.1   Development of the Exemptions Provisions

2.1   In the United Kingdom, the Radioactive Substances Act 1993 (RSA 1993) [1] previously provided the regulatory basis for the control of radioactive material and disposal of radioactive waste.

2.2   RSA 1993 was largely repealed in England and Wales with the introduction of the Environmental Permitting (England and Wales) Regulations 2010 (EPR 2010 [2]). In 2011 the Environmental Permitting (England and Wales) (Amendment) Regulations [3] repealed the remaining extant clauses of RSA 1993 and the associated Exemption Orders. The EPR (Amendment) Regulations include provisions to replace the previous exemption order suite.

2.3   EPR 2010 (as amended) provides industry, regulators and others in England and Wales with a single extended permitting and compliance system and includes those systems for discharge consenting, groundwater authorisations and radioactive substances regulation. Environmental Permitting also provides a tool for delivering the permitting and compliance requirements of EU directives such as those relating to the Batteries Directive and Mining Waste Directive*.

2.4   RSA 1993 continues to apply in Scotland and Northern Ireland. In Scotland RSA 1993 was amended through the RSA 1993 amendment (Scotland) regulations [4] and a new Exemption Order brought into effect in 2011 [5] to replace the suite of exemption orders previously applicable in Scotland†.

2.5   Although the legislative structure and wording differs between Scotland and England & Wales the two systems are intended to operate in an equivalent manner and with the same legislative controls.

2.6   To simplify references to the two new sets of legal exemption provisions under either the RSA in Scotland or the EPR in England and Wales these statutory instruments are referred to in this Good Practice Guide as the *exemptions provisions documents*.

2.7   The basis on which the various numerical values and waste disposal criteria have been developed is mainly related to the radiation dose which could be received by a member of the public, although there are exceptions to this general concept. These values are presented on a nuclide specific basis and replace provisions previously specified under the various exemption orders, notably the Substances of Low Activity (SoLA) exemption orders.

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*   EPR 2010 was further amended in 2012 to cover other permitted regimes and activities. See http://environment-agency.gov.uk/netregs/legislation/future/123325.aspx (Environment Agency website).

†   Near-identical legislation was introduced in Northern Ireland through The Radioactive Substances Act 1993 (Amendment) Regulations (Northern Ireland) 2011, Statutory Instrument No. 290 http://www.legislation.gov.uk/nisr/2011/290/made and The Radioactive Substances Exemption (Northern Ireland) Order 2011, Statutory Instrument No. 289 http://www.legislation.gov.uk/nisr/2011/289/made. There are no nuclear licensed sites in Northern Ireland and hence reference is throughout this Good Practice Guide is made only to England & Wales and Scotland.

3.2   Summary of Current Legislation and Regulatory Guidance

2.8   The exemptions provisions documents take account of and enable the UK to comply with the requirements of the European Union Basic Safety Standards (BSS Directive) 96/29/Euratom [6] (see Section 3.5.1), which itself embodies in law the recommendations of the International Commission on Radiological Protection (ICRP), particularly ICRP60 [7].

At the time of writing the BSS Directive is in the process of being revised.

2.9   The exemption provisions provide for clearance and sentencing of a wide range of articles and substances under specified conditions. *Disposals* of radioactive waste are always regulated by the Environment Agency in England and Wales or, in Scotland, the Scottish Environment Protection Agency (SEPA), regardless of whether or not a site is subject to nuclear site licence conditions. On nuclear licensed sites the *keeping and use* of radioactive material and the accumulation of radioactive waste are regulated by the Office for Nuclear Regulation (ONR) under the Nuclear Installations Act 1965 [8].

2.10   The clearance and exemptions provisions legislation is complex and in light of this the Government has produced explanatory Guidance [9]* applicable across the UK.

2.11   At the broadest level, three categories are defined within the new regime.

♦   'Out of scope' of regulation. Effectively, 'out of scope' equates to 'not radioactive' for the purposes of the clearance and exemption legislation. Articles or substances which are 'out of scope' are not subject to any regulatory requirement under this legislation† but do remain subject to all other relevant legislation (for example, based on non-radioactive properties).

♦   'Exempt from permitting'. Articles or substances which are considered to be radioactive by definition (i.e. they are not *out of scope)* but are conditionally exempt from the need for a permit or authorisation relating to their radioactive properties under EPR/RSA‡.

♦   Waste and materials subject to an environmental permit.

2.12   Wastes and materials which are out of scope or conditionally exempt remain subject to other relevant legislation (for example, based on non-radioactive properties).

2.13   The flow chart presented in Figure 2.1 reproduces the Government Guidance [9] to determine whether articles and substances are radioactive for the purposes of regulation.

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*   For ease of referencing, this is referred to simply as the 'Government Guidance' throughout this Good Practice Guide. Where other specific guidance is referenced this is identified explicitly.

†   Previous terminology referred to articles and substances which have never been contaminated or activated as 'clean' and also identified as 'excluded' articles or substances which were not 'clean' but which were below any limits subject to regulatory requirements under the Clearance and Exemption orders. The current exemptions provisions documents do not distinguish between 'clean' and 'excluded'. For the purposes of this Good Practice Guide the terms are retained to distinguish between articles or substances that have never been contaminated or activated and those that may have been activated or contaminated but measurements show to be below the out of scope limits.

‡   Many of the conditions relate to 'proper management arrangements' (for example, the need to keep adequate records [paras 3.2 & 3.3 of the Government Guidance]). If a person does not or cannot comply with the conditions, the exemption does not apply. It is the responsibility of the user to satisfy themselves that that they are exempt and users need to be able to demonstrate this to the regulators if necessary. For clarity the term 'conditionally exempt' is used throughout this Good Practice Guide.

Figure 2.1   Navigating the Government Guidance for Scope, Exemption and Permitting requirements
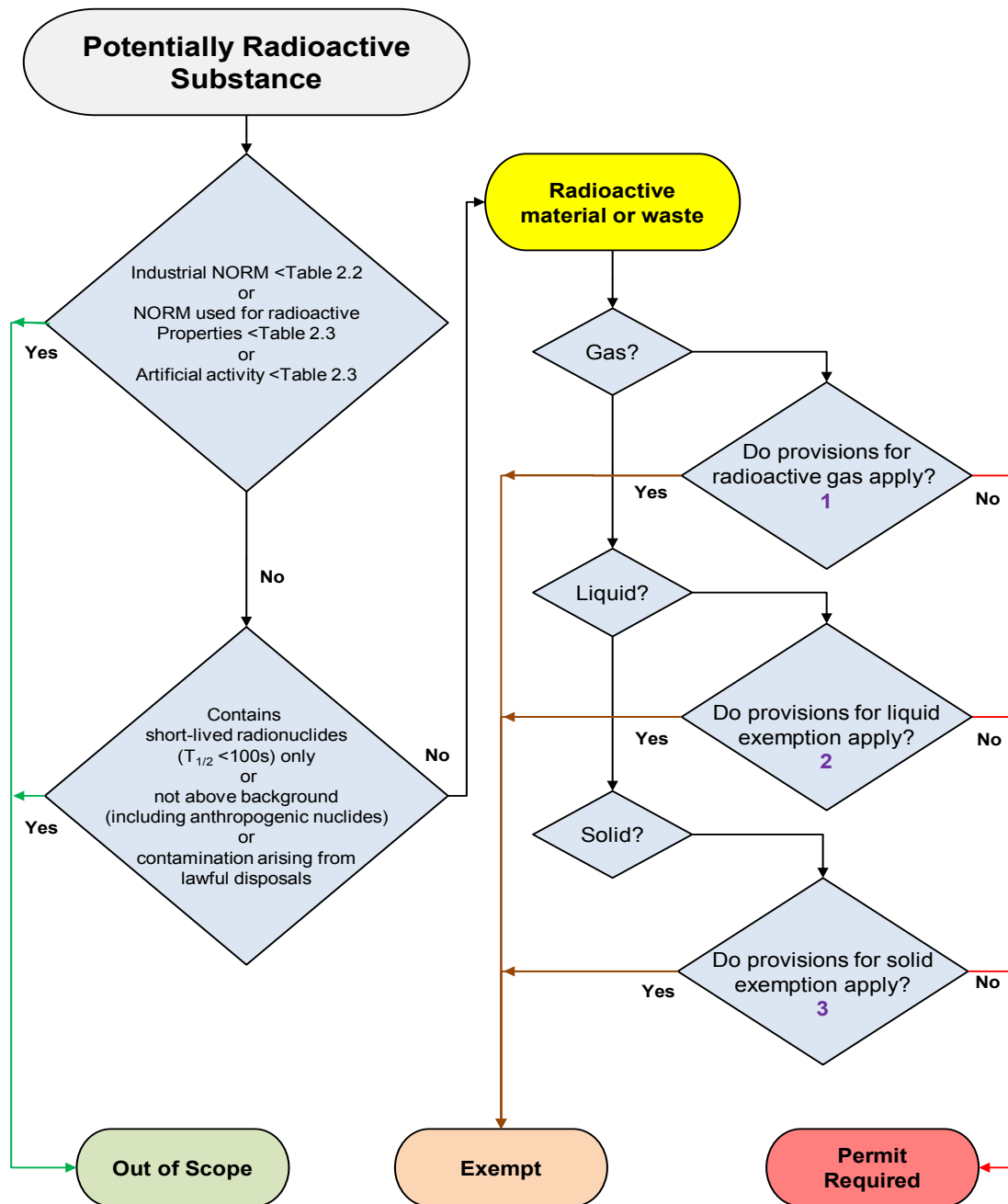
Notes:

All references to Tables and paragraph numbers refer to the Government Guidance [9].

1   Para 3.184-3.192 Disposal of ^{85}Kr and small releases when opening containers.

2   Table 3.3 (aqueous radioactive waste values), or para 3.142-3.153 (<100 ml disposal to sewer), or para 3.165-3.183 and Table 3.4 (low concentrations of aqueous waste to sewer, river or sea), excluding relevant liquids.

3   Table 3.3 (radioactive waste values of quantities an concentrations) or disposal of sealed sources, electrodeposited sources and tritiated foil sources.

All materials contaminated but remaining on the premises where contamination occurred are conditionally exempt unless these are covered by specific permit conditions.

2.14   The Government Guidance lists the exemptions that are in place for a number of situations, some of which may be applicable on Nuclear Licensed Sites. These are described in detail in that guidance and summarised in Table 2.1 below.

Table 2.1   Summary of exemptions identified in Government Guidance

Situation identified where conditional exemption may apply	Page in Govt. Guidance [9]
Keeping and use of:	
Radioactive materials – universal provisions	29[a]
Small sealed sources	33
Unsealed sources	36
Mobile radioactive apparatus	40[b]
Accumulation of:	
Radioactive waste	43
Disposal of:	
Low volumes of solid radioactive waste	47[a,c]
NORM radioactive waste up to 5Bq g^{-1}	51[a,b]
NORM radioactive waste up to 10Bq g^{-1}	54[a,b]
Waste sealed sources, tritium foil sources and electrodeposited sources	57[a]
Aqueous radioactive waste up to 100 Bq/ml to sewer	59[a]
Aqueous radioactive waste to sewer – patient excreta and compounds of radium and thorium	61[a,b]
Low concentration aqueous radioactive waste to sewer river or sea	63[a]
Gaseous radioactive waste	67[a]

a   On a nuclear licensed site may be subject to a permit issued under EPR (2010) by the Environment Agency in England and Wales, or an authorisation issued under RSA (1993) by the Scottish Environment Protection Agency in Scotland.

b   Exemption unlikely to be relevant to a nuclear licensed site.

c.   Exemption unlikely to be relevant for decommissioning sites generating large volumes of solid radioactive waste.

Note that if activity concentrations or total activities held on the premises exceed the exemption limits specified in the exemptions provisions documents, then a permit is required for all material. The exempt quantities or concentrations cannot be deducted.

2.15   For nuclear licensed sites it is likely that under most circumstances the exemptions provisions will not be relevant and the key distinction of interest is the identification of articles or substances which are out of scope.

2.16   For small users of radioactive articles or substances the exemptions provisions may be more relevant, hence reference to the terms of the exemptions is retained within this Good Practice Guide.

3.3   Interpretation of Background

2.17   Natural background embraces both radiation levels (i.e. dose rates), and activity concentrations. For the purposes of compliance with the exemption provisions documents, only radioactivity concentrations are relevant. In assessing the compliance of radioactivity concentrations with relevant limits for specified radionuclides, the *natural background* or *normal background* concentrations can be disregarded when determining if a substance exceeds the relevant concentrations.

2.18   The Government Guidance [9] provides further information on interpreting natural and artificial background and when subtraction of background is appropriate (paras 2.17-2.24, 2.37-2.43 and 4.3-4.7). The following principles associated with the definition of *normal background* apply to all naturally occurring radionuclides (such as ^{40}K), artificial radionuclides (such as ^{137}Cs), and also those which may occur both naturally and artificially (such as ^{3}H and ^{14}C).

- Normal background includes naturally occurring concentrations of radioactivity. These may be local environmental values where local materials (soils, sediments) are under assessment, or values specific to the constituents of the material or waste itself (bricks, concrete) [Government Guidance paras 2.17-2.20].

- Normal background includes widespread environmental fallout due to activities such as atmospheric weapons testing and nuclear accidents such as Chernobyl [Government Guidance paras 2.21-2.23], unless the concentration of any artificial radionuclide is above the levels 'found normally in such a substance' [Government Guidance para 4.5].

- Substances are not radioactive material or radioactive waste, where their radionuclide content is attributable to a lawful disposal [Government Guidance para 2.37], for example outside a site boundary where enhanced values are present as a result of a discharge made in accordance with the conditions and limits within an authorisation granted by the appropriate regulator. However, a substance or article may be radioactive where, following its disposal, a process occurs which was not envisioned at the time of disposal, and results in a substantial increase, or potential substantial increase, in radiation exposure to the public or radioactive contamination in the environment*.

2.19 Values used for normal backgrounds should be assessed, recorded, and justified. The provisions in the legislation which deal with artificial background are not intended to exclude localised enhanced concentrations of radionuclides which are present in the environment as a result of permitted or exempted discharges [Government Guidance para 2.24].

2.20 Practical considerations of assay need to be taken into account. If, following good practice to assay the material or waste, the measured level cannot be distinguished from the background level '*found normally in such a substance*', then the entire material can be considered as 'out of scope' [Government Guidance para 4.7].

3.4 Use of Exemption for Disposal of Solid VLLW

2.21 The Environment Agency has set out guidance on how nuclear sites can make use of the revised exemption provisions in relation to the disposal of solid "VLLW" in England and Wales. The relevant exemption provisions from the Government Guidance are defined in Table 3.3 of [9], and are reproduced below. The same exemptions defined in [9] apply in Scotland, however no guidance has been issued at the time of writing by SEPA and interpretation of some aspects may differ, for instance with respect to notification or variation.

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* The Government Guidance acknowledges that the question of what may or may not have been envisaged at the time of disposal is not straightforward but can be taken to mean those matters which may have been reasonably foreseen at the time of disposal. For example, if waste was retrieved from a solid waste disposal facility following surrender or revocation of the facility's permit, that waste would be radioactive waste [Government Guidance para 2.40]. Again, offshore sediment contaminated by historical and lawful discharges may be subject to dredging. If it is subsequently disposed further out to sea the dredgings would not be considered to be radioactive material or radioactive waste, because disposal to sea will have formed part of the original radiological impact assessment. If, however, the dredgings were brought to land for use or disposal, this could create exposure pathways which were not taken into account at the time of the original discharge and, if the consequent increase in calculated dose was substantial, then the dredgings would be considered to be radioactive material or radioactive waste respectively [Government Guidance para 2.41].

Table 2.2   Exemptions identified in Government Guidance

Radioactive waste	Maximum concentration of radionuclides	Maximum quantity of waste to be disposed of per calendar year
Solid radioactive waste, with no single item >$4x10^4$ Bq	$4x10^5$ Bq for the sum of all radionuclides per 0.1 m^3	2×10^8 Bq y^{-1}
Solid radioactive waste containing tritium and C-14 only, with no single item >$4x10^5$ Bq	$4x10^6$ Bq of tritium and C-14 per 0.1 m^3	2×10^9 Bq y^{-1}

2.22   The disposal of low volumes of solid radioactive waste is described in paras 3.80 to 3.98 of the Government Guidance [9]. Although described as "low volume" waste (indicatively based on 0.1 m^3; para 3.82 of [9]) it should be noted that disposal is in fact controlled by a combination of limits on concentration of activity and total activity, and not volume *per se*.

2.23   As stated in para 3.85 of the Government Guidance [9], nuclear operators can, in principle, make use of this conditional exemption subject to:

   ♦ the provision that all disposals of this type of waste from a site during that year can be made under the exemption (if the disposals of VLLW* exceed those limits then all such disposals need to be permitted); and,

   ♦ the wording of the permit on waste disposals.†

2.24   The exemption provisions allow conditionally exempt solid VLLW to be disposed of with substantial quantities of non-radioactive waste for burial, incineration and recovery to sites not permitted under RSR (i.e. to conventional landfills, waste incinerators and waste treatment facilities up to the limits specified in the regulations). If waste is disposed of under this provision it becomes subject to the conventional waste regime (paras 5.4 and 5.5 of the Government Guidance [9] and para 2.13 of the Government Guidance on Radioactive Substances Regulation [10]‡).

2.25   This is a change from previous guidance issued by the Environment Agency on "disposing of radioactive waste to landfill"§] following the publication of the 2007 LLW policy [11], which required all VLLW from nuclear sites to be disposed of under the consignor's permit and to sites permitted under RSR**. This guidance will be revised††.

3.5   Interactions With Other Legislation

3.5.1 The Basic Safety Standards Directive

2.26   The BSS Directive [6] sets out basic safety standards to protect the health of workers and the general public against the dangers arising from ionising radiation.

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*   For clarity, the limits in Table 3.3 of the Government Guidance refer to all forms of solid VLLW disposed of, summed over all routes.

†   Where an operator is permitted to dispose of a waste type, the operator cannot also dispose of that type of waste under an exemption.

‡   This guidance is published specifically for England and Wales and references EPR (2010), as amended; however, its general provisions will apply also to Scotland.

§   See http://www.environment-agency.gov.uk/business/sectors/100241.aspx

**   This is the consequence of treating all VLLW (including LV-VLLW) as HV-VLLW.

††   http://publications.environment-agency.gov.uk/dispay.php?name=GEHO0911BUEJ-E-E

2.27   The BSS Directive states that the effective dose expected to be incurred by any member of the public due to the exempted practice is to be 'of the order of' 10 µSv or less in a year. A figure of 30 µSv per year is recognised in European Commission documents as being the upper limit for 'in the order of', therefore where practicable, the clearance level should not result in a committed effective dose to a member of the public greater than 30 µSv per year.

2.28   The European Commission has brought forward a formal proposal for a new Basic Safety Standards Directive. The Department of Energy and Climate Change have overall UK government responsibility for negotiating the revision of the EU Basic Safety Standards Directive*.

3.5.2 The Transport Regulations

2.29   The Transport Regulations [12, 13] contain specific and relevant requirements concerning materials out of scope of radioactive substance regulation and conditionally exempt items and materials.

2.30   Internationally, the regulations for the transport of radioactive material have been developed in close co-operation with the IAEA and are based on the IAEA Regulations for the Safe Transport of Radioactive Material TS-R-1 [14]. The content of these regulations is re-formatted to enable integration into the modal regulations, as follows (for road, rail and sea).

  ♦ The European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR).

  ♦ Convention concerning International Carriage by Rail (COTIF). Regulations concerning the International Carriage of Dangerous Goods by Rail (RID).

  ♦ International Maritime Organisation (IMO). International Maritime Dangerous Goods Code (IMDG Code).

2.31   In the United Kingdom the 'Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations' [13] regulate the transport of radioactive material by road and by rail by invoking the requirements of the modal regulations (i.e. *ADR & RID*).

2.32   For the purposes of this document, the UK specific regulations above are collectively called the 'Transport Regulations', and are applicable when transport is **off** the licensed site or within the public domain.

2.33   The requirements of the Transport Regulations must always be considered BEFORE the transport of material. This is a complicated area and should be interpreted by a suitably qualified and experienced person. Industry advice is also available from the Radioactive Material Transport Users Committee (RAMTUC)†.

2.34   As general guidance only, it is noted that activity concentration limits in the transport regulations are above, or equal to, the exemption limits (and therefore are above all out of scope activity concentration limits) for all radionuclides that are also identified in Schedule 23 of EPR2011.

3.5.3 The Ionising Radiations Regulations

2.35   The Ionising Radiations Regulations 1999 (IRR 99 [15]) form the main legal requirements for the use and control of ionising radiation in the UK. The main aim of the regulations is to "establish a framework for ensuring that exposure to ionising

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*   See: http://www.hse.gov.uk/aboutus/europe/euronews/dossiers/radiationprotect.htm

†   http://www.ramtuc.org.uk/

radiation arising from work activities, whether man made or natural radiation and from external radiation or internal radiation, is kept as low as reasonably practicable (ALARP) and does not exceed dose limits specified for individuals".

2.36   The regulations effectively implement the majority of the European Basic Safety Standards Directive 96/29/Euratom [6] which, in turn, reflect the recommendations of the ICRP [7].

2.37   The regulations impose duties on employers to protect employees and anyone else from radiation arising from work with radioactive substances and other forms of ionising radiation.

3.5.4   The Environmental Protection Act

2.38   The Environmental Protection Act 1990 (EPA 1990) defines the fundamental structure and authority for waste management and control of emissions into the environment.

2.39   Part I establishes a general regime to prescribe any process or substance and set limits on it in respect of emissions into the environment. Authorisation and enforcement is the responsibility of the Environment Agency in England and Wales, and the Scottish Environment Protection Agency in Scotland.

2.40   Part II sets out a regime for regulating and licensing the acceptable disposal of controlled waste on land. Controlled waste is any household, industrial and commercial waste (s.75(4)). Part IIA was inserted by the Environment Act 1995 and defines a scheme of identification and compulsory remedial action for contaminated land.

3.5.5   Other relevant legislation

2.41   Wastes and materials which are out of scope or conditionally exempt from permitting under EPR (2010), Schedule 25, or RSA (1993) are not exempt from other legislation. For example, wastes may be classified as hazardous [16], non-hazardous or inert wastes depending on their properties, and subject to controls under EPA 90 [17] or Special/Hazardous Waste Regulations [18, 19].

3.6   References

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         mix/nuclear/radioactivity/llw-policystatement070326.pdf

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         Available from http://www.legislation.gov.uk/uksi/2009/1348/memorandum/contents

14   IAEA (2005) Regulations for the Safe Transport of Radioactive Material (Revised
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         pub.iaea.org/mtcd/publications/pdf/pub1225_web.pdf

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         http://www.legislation.gov.uk/uksi/1999/3232/pdfs/uksi_19993232_en.pdf

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         Interpretation of the definition and classification of hazardous waste. Technical
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         agency.gov.uk, www.sepa.org.uk, www.ni-environment.gov.uk

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4 Key Concepts and Practices not Specified by Regulations or Regulatory Guidance

3.1   This Chapter identifies key concepts and practices to be considered for adoption by the nuclear industry where legislation or regulatory guidance is currently considered imprecise or unclear.

3.2   Throughout this Good Practice Guide two sub-categories for articles or substances which are out of scope have been introduced, as follows.

♦   *Clean* - the article or substance has never been contaminated or activated. For example, it has been used exclusively in areas where there was no potential for activation or contamination; or there is sufficient knowledge of the management and use of the article or substance to give strong confidence that there has been no actual contamination or activation (e.g. where it was used in a contamination controlled area it was effectively protected and carefully unwrapped).

♦   *Excluded* - the article or substance has been used in areas where there is *potential* to become contaminated or activated, or where activation or contamination has occurred but has been removed or reduced to levels below out of scope activity limits.

3.3   Given an *a priori* belief that an article is either *clean* or *excluded* the main difference lies in the level of monitoring required to confirm that the article or substance in question is out of scope. For clean articles or substances, it is likely that in many cases no monitoring will be required although *reassurance* monitoring may be undertaken to provide additional evidence.

Reassurance monitoring does not imply a belief that the article or substance is radioactive, but may be used to provide evidence that the history, segregation or labelling has not been identified in error.

3.4   For excluded articles or substances there will always be a need for an appropriate depth of monitoring to confirm the belief that the article or substance can be excluded from further regulatory provision based on radiological properties*.

4.1 Articles or Substances which are 'Clean'

4.1.1 The Meaning of Clean

3.5   The majority of articles or substances used on a nuclear site will not be contaminated or activated during use and, in radiological terms, will be the same as similar articles or substances used in any work environment. It is therefore unreasonable to treat such articles or substances as radioactive, because this would unnecessarily prevent their re-use or recycling or would require an inappropriate use of disposal facilities for radioactive materials.

3.6   To become radioactive, an item or material must be either activated or contaminated. To become activated, an item or material must have been irradiated by neutrons (or, more rarely, by high energy gamma radiation).

3.7   An item or material must be considered to be potentially contaminated if it has been:

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*   Identifying an article or substance as being clean requires a very high level of confidence regarding provenance. For articles or substances which are segregated but within an area where contamination or activation may occur, it is more likely that they will be identified as excluded.

♦ in contact with a radioactive material which was not completely sealed; or

♦ in contact with a radioactive liquid or gas; or

♦ in a contamination area and has not been adequately protected from contamination; or

♦ taken from a ground or structural location where radioactive contamination is known or suspected.

3.8 For the purposes of this Good Practice Guide, an article or substance that has never been contaminated or activated is termed 'clean'.*

3.9 Articles or substances which have been contaminated or activated, but in which the radioactivity can be demonstrated to have decayed to a level below the out of scope sum of quotients (SoQ, see Section 9.1 for a fuller explanation of the term and its derivation) at the point at which they are identified as waste or a candidate for re-use or recycling, cannot be sentenced as clean but can be sentenced as out of scope (excluded).

3.10 Similarly, contaminated articles or substances should be sentenced as excluded (not clean) where the radioactivity can be demonstrated to have been removed by decontamination to levels below the out of scope SoQ at the point at which they are identified as waste or a candidate for re-use or recycling.

Note: there must be a good knowledge of the history of the article or substance in question – sentencing as clean cannot be based on monitoring alone. Materials cannot be decontaminated and then declared 'clean'.

3.11 It is acceptable practice to physically separate and segregate articles or substances so that each constituent can be treated appropriately. For example, painted steel can be segregated into the paint layer and the steel itself. The paint layer may have been exposed to contamination but provide a sufficient barrier to give confidence that the underlying metal has not been contaminated. However, in the process of removing the paint there is a potential for the metal to come into contact with contaminated paint. That is, although the steel at first consideration might be regarded as clean (see paras 3.2 and 3.8 above), it is likely that the act of removing the paint introduces uncertainty regarding the potential for contamination to have occurred (i.e. it can be identified as excluded but not as clean).

4.1.2 Clearance of Articles or Substances Believed to be Clean

3.12 If provenance alone is enough to provide strong justification that an item or material has not been activated or contaminated, measurements are only taken for reassurance (see above). In this case, it is not necessary to follow statistical guidance in Chapter 10, although professional judgement is required to decide the extent of and locations where measurements should be made.

3.13 The simple decision process identified in Figure 3.1 is followed initially for all types of articles and substances, in order to identify whether their provenance is sufficiently well established to give a high level of confidence that they are clean. This is a process which may be undertaken under a generic quality plan, often at a boundary (e.g. a barrier associated with a controlled or supervised area under IRR 99 [1]).

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* The term 'clean' does not appear in the exemption provisions documents nor in the Government Guidance (where no further distinction is made for materials and substances which are out of scope, i.e. not radioactive in law). The term clean is used here to make clear the purpose and meaning of establishing the provenance of an article or substance to determine that it has never been contaminated or activated.

3.14   Where it is decided that an articles or substance is clean but that reassurance monitoring is appropriate, sampling and measurement methods are selected according to potential activation products (which are dependent on the elemental composition of the article or substance itself and whether activation would have been caused by neutrons or photons), and/or credible contamination fingerprints. Sampling and measurement practices should follow relevant guidance in Chapters 7 and 11.

3.15   If, as expected from provenance, the item or material shows no radioactivity above relevant background levels, it is sentenced as *clean* and this completes the clearance process.*

Figure 3.1   Clearance of Articles or Substances Believed to be Clean
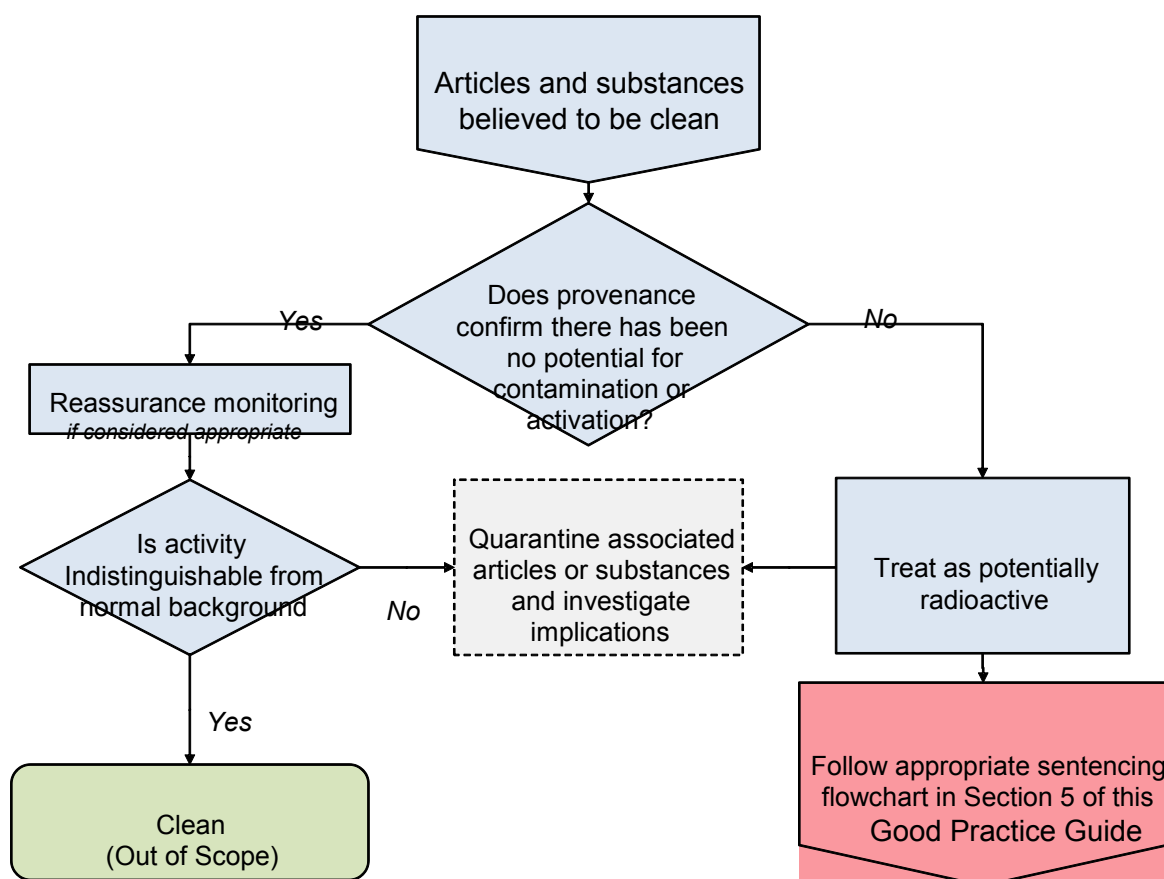
3.16   If any radioactivity is detected above the relevant background level, this must be investigated, not only because the article or substance might not be out of scope, but also because it implies a breakdown in understanding or management controls. This control failure must be identified and corrective actions taken to prevent further occurrences. The article or substance itself must be treated as potentially radioactive, and any associated articles or substances may require quarantining until it is established whether they also need to be treated as potentially radioactive.

3.17   Any article or substance found to be radioactive or potentially radioactive must be considered under Sections 6.2 – 6.5 of this Good Practice Guide, according to the nature of the radioactivity or the type of solid.

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*   For articles or substances entering a site on a temporary basis, it may be advisable to monitor at the point of entry to determine background levels of radioactivity specific to that article or substance. This may simplify later release as clean if any activity discovered can be identified as pre-existing.

3.18   If the provenance of an article or substance is not considered sufficient to justify sentencing as clean, then monitoring of the article or substance is required and sentencing must be considered under Sections 6.2 to 6.5 of this Good Practice Guide. The extent of such monitoring should be appropriate to the article or substance to be cleared.

Articles and substances cannot be decontaminated and then declared to be clean.

4.2   Dilution of Radioactivity in Solid Wastes or Materials

3.19   Deliberate dilution by mixing of wastes or materials having activities less than the exemptions provisions documents limits with other wastes and materials having activities greater than the limits, in order to achieve clearance, is not an acceptable practice.

3.20   Unavoidable dilution may occur, and is **acceptable**, where the extent of dilution is consequent on the technique employed, and the technique is designed to ensure complete removal. For example, the use of an excavator to dig out a volume of contaminated soil may result in some unavoidable mixing of soil with differing levels of contamination.

3.21   In cases where unavoidable mixing occurs, or where the distribution of radioactivity is inhomogeneous, care must be taken to ensure that any subsequent sampling or monitoring is suitably representative (see sections following and Chapters 6 and 7).

4.3   Homogeneity of Distribution of Radioactivity in Solid Wastes or Materials

3.22   The following principles should be used when analysing results from sampling of bulk wastes or materials where inhomogeneity is known or suspected and/or where an article to be cleared is made of two or more intimately bound layers (e.g. laminates or blocks and paint). A proposed process is presented in Figure 3.2. Note however, that this general approach does not replace the overall need to properly demonstrate compliance with relevant criteria.

Figure 3.2   Flowchart to Determine Requirement to Separate and Segregate

```
                        ┌──────────────────────────┐
                        │   Article or Substance   │
                        └──────────────────────────┘
                                    │
                                    ▼
                        ┌──────────────────────────┐◄───────────┐
                        │      Characterise         │            │
                        │           1               │            │
                        └──────────────────────────┘            │
                                    │                            │
                                    ▼                            │
              Yes              ◇ Homogeneous? ◇                  │
        ┌───────────────────────    2                            │
        │                          │ No                          │
        │                          ▼                             │
        │               ┌──────────────────────────┐            │
        │               │  Consider separation      │            │
        │               │  and segregation          │            │
        │               │           3               │            │
        │               └──────────────────────────┘            │
        │                          │                             │
        │                          ▼                             │
        │                     ◇ Practicable? ◇ ──Yes──► ┌──────────────────┐
        ▼                                                │  Separate and    │
┌──────────────────┐                │ No                 │  segregate       │
│ Sentence using   │                ▼                    └──────────────────┘
│ flowchart        │                                               
│ techniques       │◄──No──◇ Does Sum of Quotients ◇
│        4         │        ◇     exceed 1?        ◇
└──────────────────┘        ◇          5           ◇
                                      │
                                      │ Yes
                                      ▼
                        ┌──────────────────────────┐
                        │   Sentence as             │
                        │   radioactive waste       │
                        └──────────────────────────┘
```
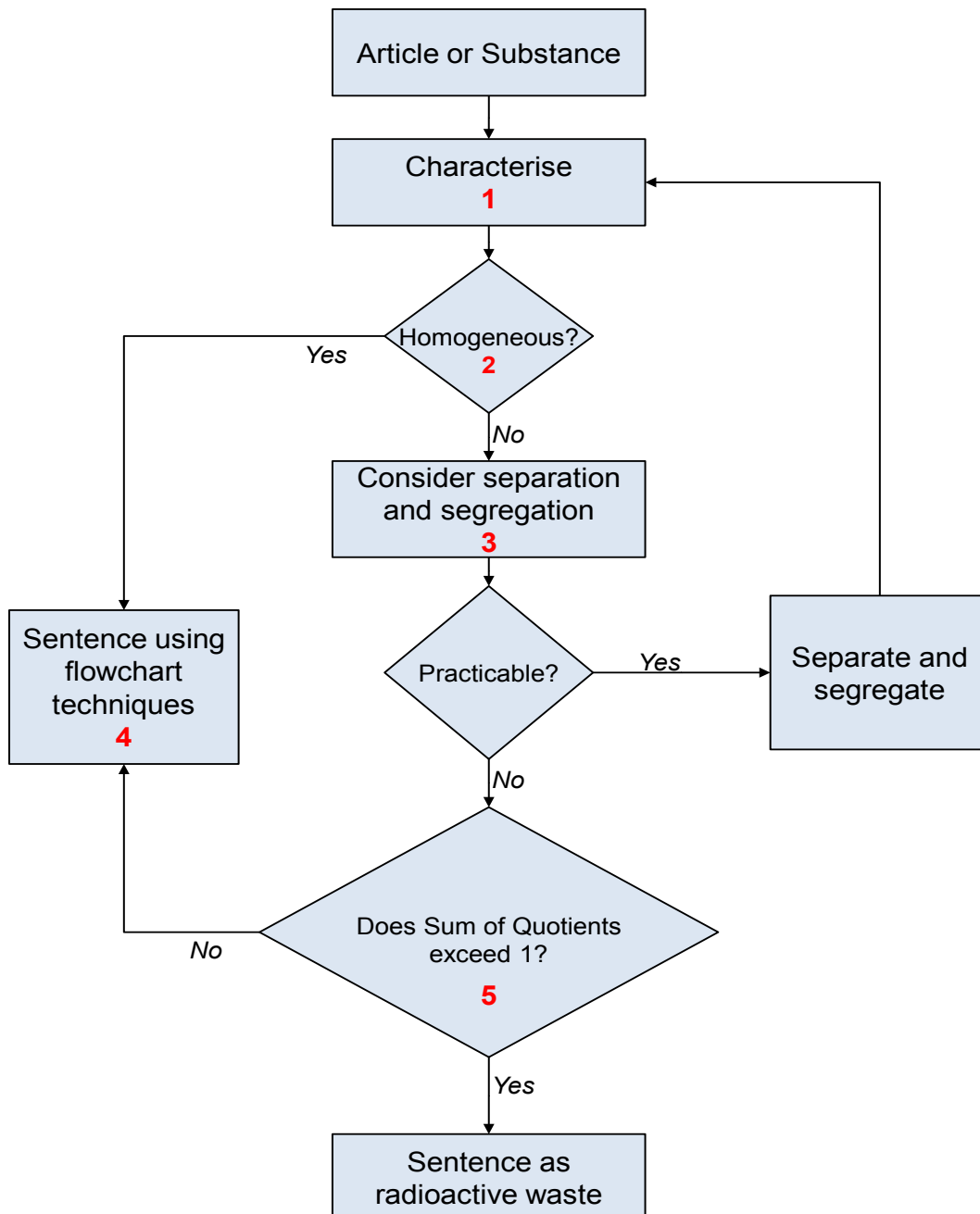
Notes

1. Characterisation means acquiring knowledge about the distribution of radioactive contamination in the waste or material.
2. A waste or material is not homogenous if there is a distinct layer (e.g. paint) or any non-homogeneities could foreseeably result in disassociation post-disposal.
3. See Table 3.1 of this Good Practice Guide
4. See Chapter 6 of this Good Practice Guide
5. Articles and substances below the out of scope limits are not radioactive for the purposes of these regulations.

3.23   If the results of samples taken from the bulk waste or material are subject to considerable variability*, then averaging over the whole waste or material volume (as a single sentencing volume) is unlikely to be acceptable without proper (documented) consideration of:

    i.   the practicability of segregation and separation;

    ii.   suitable revision of monitoring and numbers of samples (See Chapter 7);

    iii.   suitable reduction in the size of each sentencing volume;

    iv.   whether it is practicable to make further measurements to identify each area or volume containing significant concentrations of radioactivity;

    v.   whether it is practicable to remove or segregate small areas or volumes containing significant concentrations of radioactivity (hot spots);

    vi.   the potential radiological significance of inhomogeneity.

3.24   Practicability should take into account factors such as:

♦   the costs in terms of effort, time and resources involved in undertaking separation and segregation;

♦   the conventional hazards and risks to the workforce undertaking the separation and segregation (e.g. due to the presence of hazardous substances such as asbestos, or properties such as flammability);

♦   for wastes, the impacts against these parameters of disposal as radioactive waste (LLW, VLLW where available) or as cleared waste must be considered.

3.25   In considering suitable scenarios against which to determine the radiological detriment, the onward use, disposal conditions or other endpoint† for the waste or material should be considered. For example:

♦   where material is intended for re-use or recycling, the potential radiological impact should be assessed using a *conservative* modelling approach;

♦   where waste is to be disposed of to a landfill facility, the potential radiological impact should be assessed using a *realistic* modelling approach.

3.26   In cases where the potential radiological significance of excluding a waste or material would exceed a dose of the order of 10 µSv per year to an exposed member of the public (see para 2.27 for clarification of the meaning of a dose 'of the order of' 10 µSv), clearance is NOT permissible. In this case, if practicable, either further separation or segregation is required, or the total volume should be disposed or treated as waste in accordance with UK LLW Strategy [2].

3.27   In some cases it may not be practicable to remove areas of relatively higher activity/hot spots, although the overall radiological significance is negligible. In these cases, recognising public and business perceptions, it may be appropriate to sentence the waste or material conservatively as radioactive.

3.28   Table 3.1 contains a summary of outcomes compliant with this Good Practice Guide for materials with inhomogeneity of radionuclide distribution.

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*   What constitutes considerable variability will be dependent on the number of samples, analytical limits of detection for relevant radionuclides and the margin with respect to relevant limits or thresholds. As a rule of thumb results would be considered acceptable where no individual sample measurement exceeds 5 SoQ <u>and</u> where the average is <0.75 SoQ.

†   In this case, endpoint means the end of 'duty of care' considerations.

Table 3.1   Indication of potential outcomes

Surface Layer[a]	Bulk layer[b]	Overall Average	Code Compliant Outcome
Average <relevant limits	Average <relevant limits	<relevant limits	No radiological requirement to undertake separation and segregation prior to clearing waste, although commercial considerations (e.g. recycling or re-use options) should be considered.
Average >relevant limits	Average <relevant limits	<relevant limits	Separation and segregation should be undertaken unless a justification can be made that removal is not reasonably practicable, the expenditure (whether in time, trouble or money) is grossly disproportionate to the safety and environmental benefits gained, and the overall impact of disposal is less than 10 μSv per year.
Average <relevant limits	Average >relevant limits	>relevant limits	Unless commercial considerations (e.g. recycling or re-use options) for the 'out of scope' surface layer are sufficient to justify the safety and environmental impacts of separation and segregation, it would be expected that articles or substances in this configuration would be managed as radioactive waste in accordance with the UK LLW Strategy.
Average >relevant limits	Average >relevant limits (Bq g^{-1})	>relevant limits	Manage as radioactive waste in accordance with UK LLW Strategy.

a.   For example, paint, laminate or region of increased radionuclide concentration.
b.   For example, brick, blockwork or metal structure components.

4.4   Confidence Levels for Sentencing

3.29   Nothing in the following paragraphs should be applied in isolation from the detailed requirements for statistical analysis presented in Chapter 11.

3.30   Decisions should be taken so that the probability that a radioactive article or substance is incorrectly sentenced as non-radioactive (i.e. a "false negative") is very low and will generally be lower than the probability of a non-radioactive article or substance being sentenced incorrectly as radioactive (i.e. a "false positive")

3.31   In the absence of other guidance, the confidence levels sought typically should be:

   i.   there is <5% probability that the *sentencing volume* of a radioactive article or substance has been incorrectly sentenced as *non-radioactive* (false negative)

   ii.   there is <20% probability that the *sentencing volume* of a *non-radioactive* article or substance has been incorrectly sentenced as radioactive (false positive)

3.32   Determination of the number of samples necessary is discussed in Chapter 11.

4.5   Sentencing and Compliance Volumes

3.33   The *sentencing volume* of an article or substance is the volume (or part of an article) over which an individual sentencing decision is taken.   The sentencing volume should be chosen or adjusted to satisfy homogeneity limitations and confidence level requirements (see Section 4.3, above).

3.34   The sentencing volume over which the radioactivity concentration is averaged, in order to meet the requirements of the exemption provisions documents, is often set

by practical considerations such as the unit of volume in which the article or substance will be transported. It will usually represent a single arising, or arisings of a very similar nature. The sentencing volume should be sufficient to justify that it will be sufficiently representative. Where practicable, the sentencing volume should be agreed with the regulator and recorded formally. In general, larger sentencing volumes are acceptable for arisings where contamination is reasonably uniform and smaller sentencing volumes where inhomogeneity is significant.

3.35   If the average activity of a sentencing volume is determined to be less than the exemption or out of scope limit, but not within the specified confidence level (i.e. 95%) it is acceptable to bulk two or more similar sentencing volumes to produce a larger *compliance volume* in order to meet the desired level of confidence for the final disposal volume.

3.36   This is not dilution as it is undertaken after sentencing. The purpose is solely to improve confidence levels, not to alter the apparent characteristics of the waste or material.

3.37   The approach to determining sentencing areas is laid out in ISO 7503, part 1*.

4.6   Surface Contaminated Items and High Surface Area to Volume Items

3.38   Impervious solid items (wastes or materials) with no inaccessible surfaces, voids or potential pathways for contamination ingress are called potentially *surface contaminated items*. Radioactive contamination on such items is generally detectable by external measurements (monitoring and/or wiping).

3.39   Exceptions occur when the contaminating radioisotope is able to migrate into the material (e.g. tritium), or when the item has been activated rather than contaminated. These items should be considered as potentially tritiated solids or potentially activated solids (see Section 6.4) as appropriate. Articles and substances potentially contaminated by other radionuclides capable of diffusing into them (e.g. caesium), should not be considered *surface contaminated items* if their total radioactivity cannot be quantified by external measurements alone (see Sections 6.2 and 6.3).

3.40   Some *surface contaminated items* have a large ratio of surface area to volume and these are termed *high surface area to volume items*. There is no rigid delineation of this grouping, neither is one necessary, but paper, card, plastic sheeting and clothing are within this group and glass and thin metal sheeting of low to moderate density may be included.

3.41   The importance of identifying *surface contaminated items* and *high surface area to volume items* is that they are often cleared and sentenced by external monitoring and wiping only. However this is a simplification which can lead to inadvertent non-compliance with relevant exemption provisions, so both surface and consequential average bulk contamination assessment of these particular items must be considered carefully, as explained below.

4.7   Surface Clearance Levels

3.42   For the purposes of clearance of articles from regulatory control under the exemptions provisions documents, compliance with bulk activity concentration limits

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*   ISO 7503-1:1988. Evaluation of surface contamination -- Part 1: Beta-emitters (maximum beta energy greater than 0,15 MeV) and alpha-emitters.

is **always** necessary and is the prime requirement of the clearance and exemption legislation. This is not, however, considered to be sufficient because there are additional concerns regarding handling safety and the potential to spread contamination. These concerns are primarily for *surface contaminated items* where radioactivity may be concentrated on surfaces.

3.43   In general, surface contamination is regulated by IRR 99 [1], although IRR 99 has no quantitative limits for acceptable levels of surface contamination*.

4.7.1   Derivation of Reference Surface Clearance Levels

3.44   The purpose of introducing risk-informed exemption values in the exemptions provisions documents is to align UK legislation with the European Basic Safety Standard Directive 1996 [3]. This states that the effective dose expected to be incurred by any member of the public due to the exempted practice is to be 'of the order of' 10 µSv or less in a year. As noted in Section 3.5.1, an upper dose level of 30 µSv in a year is held to be compatible with this objective.

3.45   A robust dose model should underpin the derivation of any surface clearance levels. It should be endorsed by an appointed Radiation Protection Adviser (RPA)† or Radioactive Waste Adviser‡ and, if the dose model and surface clearance levels are to be representative of **all** cleared items, the assumptions used need to be suitably conservative to allow for any variations in factors.

3.46   The dose model should take into account the following.

i.   The types of wastes or materials to be cleared.

ii.   Whether a dose model already exists for the substance to be cleared (e.g. RP89 [4] for metal re-use, RP101 for surface clearance [5] and RP113 [6] for concrete and rubble re-use), in which case the surface clearance levels stated in these documents can be used§.

iii. Different pathways and scenarios that could result in a member of the public receiving a dose from the cleared items.

iv.   The fingerprint (see Chapter 10) and the dose co-efficient for that fingerprint.

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*   The *Referenced Surface Clearance Levels* specified in Issue 1 of the NICoP should **no longer** be used for clearance of items or materials from regulatory control <u>unless</u> justified, and documented, as applicable to your circumstances. Such justification will include demonstrating that the surface contamination levels (i.e. activity per unit area) are consistent with the activity concentrations limits (i.e. activity per unit mass).

†   IRR99 specifies particular matters on which radiation employers should seek advice from a suitable RPA. HSE has issued advice on the criteria of competence to meet the requirements of an RPA, and on issues requiring advice from an RPA. See: http://www.hse.gov.uk/radiation/rpnews/rpa.htm

‡   The designation Radioactive Waste Advisor satisfies the requirement under European law for people who keep or use radioactive material, or who accumulate or dispose of radioactive waste, to appoint advisers, known as "qualified experts", to advise them on radiological protection. In the UK we call the qualified expert for radioactive waste management and environmental radiation protection a 'Radioactive Waste Adviser'. For information issued by the Environment Agency, see: http://www.environment-agency.gov.uk/business/sectors/32517.aspx. For information issued by SEPA see: http://www.sepa.org.uk/radioactive_substances/radioactive_waste_advisers.aspx. The requirement is the same in England and Wales and in Scotland.

§   Note: these models are specific to the substances to which they refer; they are not appropriate for other types of substance.

3.47   Organisations should **define, and justify, their own surface clearance levels** for use when clearing items, materials or wastes in accordance with the steps set out above. See appendix F for a worked example.

3.48   There may be some cases where the surface clearance levels determined using this methodology for certain radionuclides and waste types are not achievable using currently available technology. In this instance it may be acceptable to justify higher surface clearance levels providing that the equipment being used represents BAT for assay of the items in question*.

3.49   In other cases, a situation may arise where the surface clearance level for a metal waste could meet all of the above criteria, but still have the potential to set off a gate monitor. In order to ensure that a metal recycling facility accepts the metal, it may be necessary to invest some effort into explaining the purpose and scope of the clearance and exemptions legislation to the supply chain or in identifying an alternative route for transfer or disposal of the waste. There are cost advantages to making use of direct recycling routes, rather than managing the waste as LLW. However, stakeholder considerations also need to be taken into account when justifying surface clearance levels.

4.7.2 Monitoring for Compliance with Surface Clearance Levels

3.50   Once the surface clearance levels have been defined there is an expectation that appropriate instruments are used to assess the activity on the surface of the item. Measurement instruments should use a response factor that is appropriate to the nuclides being detected and can achieve the desired detection limits. Consider using *in-situ* monitoring equipment in integrated count mode to get a lower detection limit if required. In cases where it is not possible to use a probe or hand-held instrument, consider taking surface samples.

3.51   It is considered to be best practice to remove all non-fixed contamination prior to sentencing. Organisations should have a robust justification for not undertaking this activity.

4.8   References

1   The Ionising Radiations Regulations 1999. Statutory Instrument 1999 No. 3232. The Stationery Office. Available from:
        http://www.legislation.gov.uk/uksi/1999/3232/contents/made

2   Defra, DTI, Welsh Assembly Government, Scottish Executive, DoENI (2007) Policy for the Long Term Management of Solid Low Level Radioactive Waste in the United Kingdom. Defra, London. Available from:
        http://www.decc.gov.uk/en/content/cms/meeting_energy/nuclear/radioactivity/waste/low/low.aspx

3   European Union Basic Safety Standards Directive 96/29/Euratom. Available from:
        http://ec.europa.eu/energy/nuclear/radioprotection/doc/legislation/9629_en.pdf

4   European Commission (1998) Recommended radiological protection criteria for the recycling of metals from the dismantling of nuclear installations, Radiation Protection No. 89, 1998. Available from:
        http://ec.europa.eu/energy/nuclear/radiation_protection/doc/publication/89.pdf

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*   Caution will be required for clearance of items with surface contamination by radionuclides which may give rise to a relatively high dose but are hard to detect. In addition to the use of BAT for detection, the maximum missable activity will need to be determined, together with the associated potential dose.

5   European Commission (1998) Basis for the definition of surface contamination
           clearance levels for recycling or reuse of metals arising from the dismantling of
           nuclear installations. Radiation Protection No. 101, Luxemburg 1998, ISBN 92-828-
           5098-6. Available from:
               http://ec.europa.eu/energy/nuclear/radiation_protection/doc/publication/101.pdf

6   European Commission (2000) Recommended radiological protection criteria for the
           clearance of buildings and building rubble from the dismantling of nuclear
           installations. Recommendations of the group of experts set up under the terms of
           Article 31 of the Euratom Treaty. Radiation Protection 113. Available from:
               http://ec.europa.eu/energy/nuclear/radiation_protection/doc/publication/113.pdf

5   Management Principles and Arrangements

4.1   The aim of government policy for the management of items, materials and wastes is to achieve *sustainable development*. For wastes in particular, application of the waste hierarchy is also applicable. In response to these aims and guidance, the following objectives are identified:

♦   to avoid where possible, and otherwise minimise, the creation of radioactive items and materials;

♦   to avoid where possible, and otherwise minimise, the creation of all wastes, including *clean* and *conditionally exempt* wastes, and to maximise the quantities of potentially radioactive items and materials that may be correctly cleared as *clean* or *conditionally exempt;*

♦   to maximise re-use and recycle options and minimise the need for disposals;

♦   to achieve a high level of safety in all disposals;

♦   to have a high level of confidence that sentencing is technically correct and is demonstrably safe;

♦   to undertake these activities in compliance with all relevant legislation; and,

♦   to achieve the above effectively and efficiently.

4.2   These objectives are achieved in part by preventing and controlling surface contamination, which is legislated and regulated by the Office for Nuclear Regulation (ONR) under the Ionising Radiations Regulations 1999 [1] and its associated Guidance [2], and by licence conditions in nuclear site licences. These regulations therefore have relevance to the minimisation of radioactive wastes and are also the origin of the requirement to justify exposures and keep radiation doses and risks as low as reasonably practicable (ALARP).

4.3   In addition, permits or authorisations for discharges, disposals and transfers granted by the environmental regulators (EA and SEPA) under EPR 2010 / RSA 93 always contain a mandatory requirement to apply best available techniques (BAT), for permits issued under EPR in England and Wales, or the equivalent best practicable means (BPM), for authorisations issued under RSA in Scotland, to the management and minimisation of waste.

4.4   In support of these objectives, the management principles and arrangements described in the remainder of this Chapter are to be adopted. A nuclear industry Good Practice Guide on the application of BAT for the management of radioactive waste is available [3]*.

5.1   Safety and Environmental Principles

5.1.1 BAT and Minimisation of Waste/Contamination

4.5   It is a requirement within permits issued under EPR that the Operator shall minimise the activity of radioactive waste that will require disposal and, where disposal is required, shall do so in a form and manner so as to minimise the radiological effects on the environment and members of the public. Under the Nuclear Installations Act [4] standard licence condition 32 [5] also requires adequate arrangements to

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*   This guidance is also applicable to the requirements of establishing BPM for the management of radioactive wastes as the two regimes are broadly equivalent.

minimise the rate of production and total quantity of radioactive waste and to record such waste.

4.6 Adoption of the waste hierarchy is embedded in UK policy for the management of solid, liquid or gaseous radioactive wastes [e.g. 6, 7, 8, 9, 10]. The waste hierarchy means:

♦ not creating waste where practicable;

♦ reducing waste arisings by activity, mass or volume to a minimum through the design and operation of processes and equipment, including effective waste characterisation, sorting and segregation, volume reduction and removal of surface contamination;

♦ minimising quantities of waste requiring disposal through decay storage, re-use, recycling or incineration (including recovery of energy from waste schemes).

4.7 Disposal of waste is always the least preferred option [11]. Where disposals are necessary, BAT should be applied to minimise impacts (Figure 3). Options for the management of radioactive waste include discharge of gaseous or liquid radioactivity into the environment ('dilute and disperse') or trapping in a solid, concentrated form for storage and eventual disposal ('concentrate and contain').

4.8 BAT should be used to minimise potentially radioactive arisings and in all significant treatment, clearance and sentencing activities, while radiation doses and risks should be kept as low as reasonably practicable (ALARP).

4.9 BAT should be used to reduce or remove contamination on or within items and materials to be cleared as *conditionally exempt*, subject to the principle that radiation exposures are kept as low as reasonably practicable (ALARP).

4.10 An holistic approach should be used in waste management. If significantly more waste, or an intractable waste, will be created by decontamination, or if an item or material cannot be economically decontaminated, it may be best practice not to decontaminate it but to sentence it as radioactive waste.

4.11 Where practicable, the Government's view is that 'concentrate and contain' is generally appropriate for managing radioactive wastes, although if it can be demonstrated that a 'dilute and disperse' option is BAT, such an option could be preferred.

4.12 Where it is demonstrably safe to do so, all waste management arrangements should seek to minimise the need for all disposals (especially of radioactive wastes) and maximise the use of processes that encourage the re-use and recycling of materials.

4.13 To the best belief of the operator, the release of items or materials from regulatory control should have no significant impact on human health or the environment. The operator must recognise that wastes or materials sentenced as *clean*, *excluded* or *conditionally exempt* remain subject to other relevant regulations, and the operator retains a duty of care until re-use, recycling or final disposal has taken place.

4.14 No item or material should be released from control unless there is adequate recorded evidence that it has been correctly sentenced. Sentencing decisions should always be made conservatively.

5.1.2 Treatment and Production of Quality Plan

4.15 If release is not permitted, further treatment should be considered. This will require a quality plan to be produced, which may be simple or complex according to circumstances. The plan should define the chosen outcome using all available information to consider all practicable treatment options (including precipitation of dissolved radioactive solids, if applicable, and both onsite and offsite treatments),

whether they satisfy BAT and ALARP, their cost-effectiveness and the availability of destinations for the arisings.

♦ If treatment onsite is the best option, the plan should include the measurements required, how they will be assessed, and decision regimes. Measurement practices should use guidance in Chapter 6.

♦ If treatment is to be undertaken offsite, much less detail may be necessary in the quality plan.

♦ If no suitable treatment can be identified which is likely to result in a route for disposal for arisings, it may be necessary to store them until one is available.

4.16   If a suitable treatment is identified, this is described in the quality plan, and proposals should be submitted to Company management and/or the regulators informed of them as necessary prior to undertaking it. For treatments undertaken onsite, liquid arisings are re-measured after treatment against the same criteria as before; radioactive solid arisings (following cementation for example) will follow appropriate disposal procedures. For treatments to be undertaken offsite, authorised transfer is required. If this is not available, the liquid will have to be stored onsite until an authorisation is obtained.

5.2   Principles for Plant Operation

4.17   Plant should be designed, and operations involving radioactivity and radioactive materials should be carried out, if possible, to prevent or otherwise to minimise the activation or contamination of the items and materials used (and the plant itself).

4.18   Plant, items and materials should be designed and used, as far as practicable, in ways to facilitate their subsequent decontamination, if this becomes necessary.

4.19   Plant, items and materials likely to become activated or contaminated should be managed and controlled throughout their life, and their history accurately recorded to support and simplify eventual clearance or sentencing processes.

4.20   All such items and materials should be identifiable throughout their life and they should remain segregated or separable where practicable if this will simplify later treatment and sentencing.

4.21   The spread of radioactive contamination in general should be prevented by delineating and controlling all access and egress to areas which have the potential to become, or are, contaminated by radioactivity. These areas will usually be static locations (whether temporary or permanent), but could for example be the inside of a containment which is transportable.

4.22   Such areas should themselves be monitored regularly so the actual extent and nature of any contamination present is known. They should always be kept as clean as reasonably practicable as the principal defence against spread of radioactivity and contamination to items and materials.

4.23   Items and materials should only be introduced into such areas if this is essential to operations and they must then be controlled until formally cleared or sentenced.

4.24   Additional care should be taken where practicable to avoid contamination of high surface area to volume items and materials (principally paper, plastic sheeting and personal clothing) where subsequent clearance is intended, as monitoring of such items may be complex (see Section 6.3).

4.25   The management principles outlined above should be the first lines of defence, and an appropriate monitoring regime (usually monitoring and wiping) during clearance of potentially *surface contaminated items* from the area should be for reassurance

as the last line of defence to confirm that management arrangements have been adequate.

5.3   Quality Assurance Arrangements

4.26   Quality systems should require personnel to be trained as appropriate in the procedures to be followed, and in the use, calibration and maintenance of monitoring equipment.

4.27   Quality systems should be subject to company audit programmes and procedures and records should be open to scrutiny by regulators and should address, in particular, the following requirements.

♦   Articles and substances with the potential to become radioactive should be identifiable and should have an owner at all times, with responsibilities for its overall control, maintaining segregation and separability when this will be advantageous for later clearance, and for recording and keeping documentation on its history of use.

♦   Maintenance of adequate records, for example, to include:
    o   clearance certificates;
    o   other records which demonstrate and justify the clearance and sentencing decisions for items and materials and conformance to the principles and practices given within this Good Practice Guide; and
    o   records of quantities and types of material or waste cleared.

♦   Clearance systems should place clear responsibilities on individuals, especially for decision taking.

♦   Relevant decision criteria employed in sentencing should be specified and traceable to this Good Practice Guide.

♦   In general, clearance certificates should be issued for offsite re-use, recycling and disposal and under all other circumstances deemed necessary. Company procedures should identify these circumstances.

♦   Where clearance certificates are issued with articles or substances, they should include the following features:
    o   unique identification (as far as practicable) of the item or material cleared;
    o   identification of the documentation which supports the certificate;
    o   identification of the legislation with which it is compliant (e.g. EPR11, IRR 99, RSA 93, CDG09 *etc*)
    o   a statement of caveats where applicable;
    o   a statement of recommendations by and signature of a nominated suitably qualified and experienced person (SQEP) concerning compliance with legislation and future use or disposal;
    o   authorisation by and signature of the owner of the item or material;
    o   a date of issue and period of validity of the certificate;
    o   a statement of responsibilities for keeping the documentation and certificate
    o   a signed confirmation of release and date;
    o   the statement "For all regulatory and control purposes, this is not radioactive waste/material".

♦   The condition of articles and substances for which clearance certificates have been issued, and the validity of the certificates.

4.28   Operators should have arrangements to ensure consistency of application of this Good Practice Guide, in particular across large or complex sites.

4.29   Systems and procedures must be practicable and proportionate.

5.4 Clearance and Sentencing Arrangements for Items and Materials

4.30   Clearance processes should follow the relevant Flowcharts and guidance in Chapter 6 of this Good Practice Guide.

4.31   All sentencing and clearances must comply with relevant limits under the exemptions provisions.

4.32   In considering clearance under EPR 2011 / RSA 93, the requirements for exclusion from regulatory control under the Ionising Radiations Regulations [1]), the Carriage of Dangerous Goods Act [12] and the Carriage by Rail Regulations [13] (see Chapter 3) must also be satisfied for full uncontrolled release of the item or material to be permitted.

4.33   A generic or individual quality plan is required for each significant waste treatment, clearance and sentencing operation (unless it can be shown that one is unnecessary).

4.34   Quality plans drawn up in accordance with the quality management system should include the following:

♦   The activities (treatments, measurements, assessments & sentencing), and the sequence of activities, to be carried out;

♦   The procedures and instructions to be followed for the activities;

♦   The inspection activities hold and decision points;

♦   Relevant responsibilities for all activities, inspections, decisions and authorisations, and

♦   The documentary and record keeping requirements and responsibilities.

4.35   Simpler procedures may be adopted for the sentencing of items and materials that are *clean* (i.e. where they have not been contaminated or activated) compared to those procedures for sentencing items and materials that are potentially radioactive. When doubt exists, items and materials must not be assumed to be *clean*.

5.5 References

1   The Ionising Radiations Regulations 1999. Statutory Instrument 1999 No. 3232. The Stationery Office. Available from:
http://www.legislation.gov.uk/uksi/1999/3232/contents/made

2   HSE. Work with ionising radiation. Ionising Radiations Regulations 1999. Approved Good Practice Guide and guidance. Available as a download from:
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3   Nuclear Industry Safety Directors Forum. Best Available Techniques (BAT) for the Management of the Generation and Disposal of Radioactive Wastes. A Nuclear Industry Good Practice Guide. Available from:
http://www.rwbestpractice.co.uk/html/Code%20of%20Practice%20Issue%201%20_2010%2011%2008_.pdf

4   Nuclear   Installations   Act   1965   (as   amended),
http://www.opsi.gov.uk/RevisedStatutes/Acts/ukpga/1965/cukpga_19650057_en_1

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6   Environment Agency (2009). Nuclear Sector Plan, Environmental Sector Plan for the Nuclear Industry, Issue 2.   http://publications.environmentagency.gov.uk/pdf [9-1]EHO0709BQGI-e-e.pdf

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6 Clearance and Sentencing Processes

6.1 Overview of Sentencing Process for Radioactive or Potentially Radioactive Articles or Substances

5.1 Figure 5.1 (overleaf) is an illustrative overview of the clearance and sentencing routes for all types of potentially radioactive materials (solids, liquids and gases). It identifies the sentencing routes to be followed for any item or material, including any secondary or changed form arisings that could be produced from its treatment, and the range of possible outcomes which can result.

5.2 Articles or substances which are believed to be clean should follow the procedures for clearance identified in Section 4.1.

5.3 Sentencing of solids is much more complex than sentencing of relevant liquids or gases because of the variety of types of solids, the greater potential for solids to conceal radioactivity (including both small and large particles), the greater potential to contain a high degree of non-uniformity, the larger number of options for monitoring and sampling, and the greater complexity of, and potential for, treatment. Sentencing of solids therefore follows a number of possible routes.

5.4 Solid items are sentenced according to the first of the following Sections 5.2 – 5.5 which is applicable, depending on the type of solid or nature of the potential radioactivity associated with it.

5.5 For nearly all solids, the possibility that surface coatings (paint or otherwise) may cover radioactive contamination which cannot be detected through them must be considered. Surface scrapings or other techniques may be necessary to determine whether this has occurred and whether surface stripping is desirable or practicable. Such contamination must be quantified as part of the assessment. This is not considered explicitly in the flowcharts.

5.6 It may be justifiable to crush some solids to facilitate measurements.

5.7 For relevant liquids (see Section 5.6), complexities occur when the liquid is a mixture of immiscible liquids or is associated with significant (visible) amounts of insoluble solids, including suspensions of fine particulate. Such liquids are analysed by initially following Section 6.6.2. Where both phases (liquid and solid) separately meet the clearance criteria, then it is not necessary to segregate the item for the purpose of sentencing.

5.8 If one or more of the phases is radioactive, and their separation by physical or chemical means would be practicable, it is necessary to know where the radioactivity resides to identify the best practice for subsequent treatment. Where the liquid has no visible solids (or following separation from solid material), Section 5.6.3 should be followed.

5.9 Sludges form a special case (see Section 5.7) as they cannot be treated as 'liquids containing suspensions' since the solid phase may dominate in terms of mass or volume but, typically, contain more liquid than would normally be compatible with classification as a solid.

5.10 Section 5.8 is applicable where a gas is held for clearance and sentencing purposes. Continuous discharge processes are not within the scope of this Good Practice Guide.

Figure 5.1   Overview of Radioactive Material Sentencing
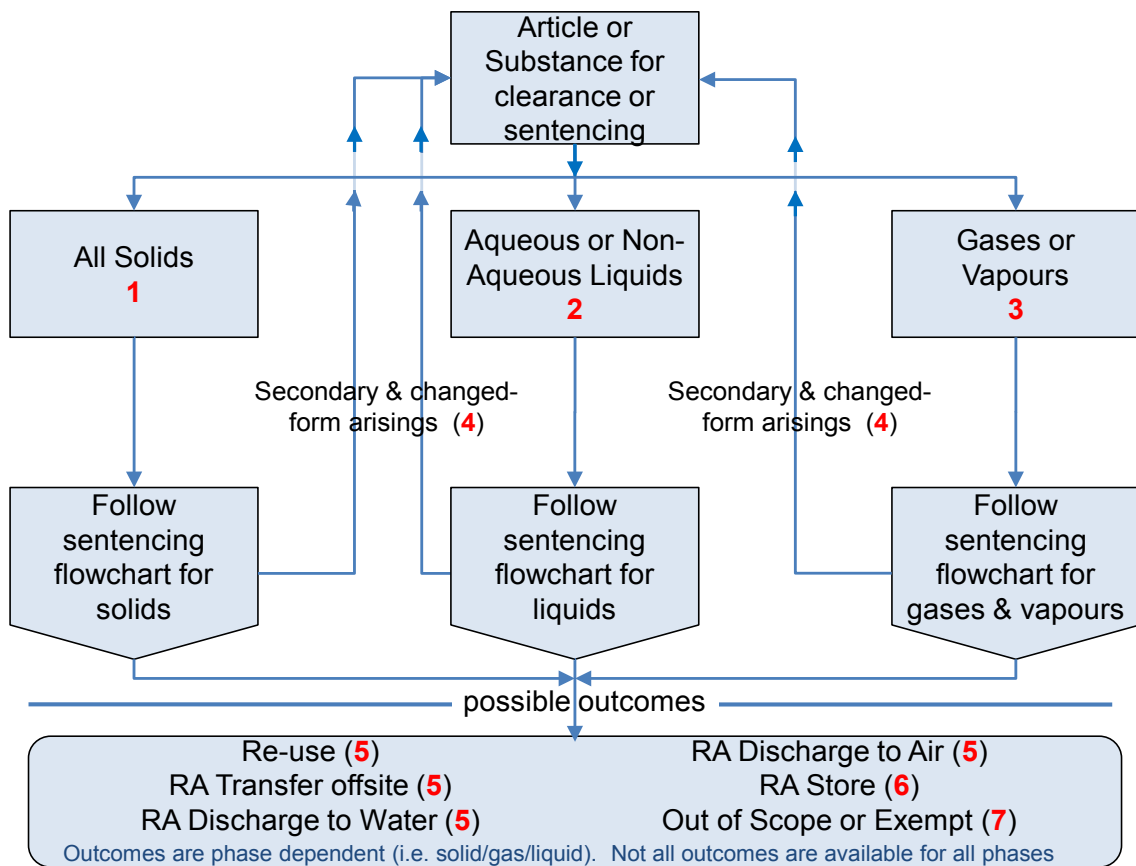
Notes

1. Including surface contaminated items, high surface area to volume items, materials and clothing.
2. Including sludges and suspended solids.
3. Including aerosols and particulates.
4. Secondary arisings of the same or different form can be produced from physical and chemical treatments (e.g. segregation, washing, scrubbing, solidification, incineration).
5. Transfer or discharge is subject to EPR 2010 permit given by EA or RSA 93 authorisation given by SEPA. Transfer may be to another site for processing for recovery or for disposal.
6. If no disposal route is available, storage may be the only option.
7. Both out of scope and conditionally exempt materials or wastes do not require permitting under EPR 2010 or RSA 93 but are subject to relevant legislation and guidance for non-radioactive materials and wastes.

5.11   As stated in the following individual sections, in all cases measurements made should use the guidance given in Chapters 8 and 9 and statistical analysis should use the guidance given in Chapter 10.

6.2   Sentencing of Potentially Surface Contaminated Items

5.12   Where the provenance of a solid item does not justify it being considered clean (i.e. it is a radioactive or potentially radioactive solid) and it is an item which is impervious with accessible surfaces, it is provisionally identified as a potentially surface contaminated item (SCI). Sentencing SCIs follows the flowchart process identified in Figure 5.2, unless the following provisions apply.

♦   If the item has a *high surface area to volume* (including personal clothing), whether it is strictly impervious or not, it should be sentenced by following the process identified in Section 5.3.

♦ If the item is potentially *activated*, or has had potential contact with *tritium*, it should be sentenced following the appropriate process outlined in Sections 5.4.1 and 5.4.2.

♦ If the item has had the potential to have been contaminated by a diffusive radioelement such as caesium, which could have permeated the surface, consideration has to be given to whether the radionuclide(s) can be detected and quantified, and the item sentenced, by surface measurement only. In cases where this is uncertain, the process identified in Section 6.4.4 (for a porous solid) should be used. Where the item is complex, or has inaccessible surfaces, the process identified in Section 6.5 should be followed.

Figure 5.2   Clearance of Potentially Surface Contaminated Items
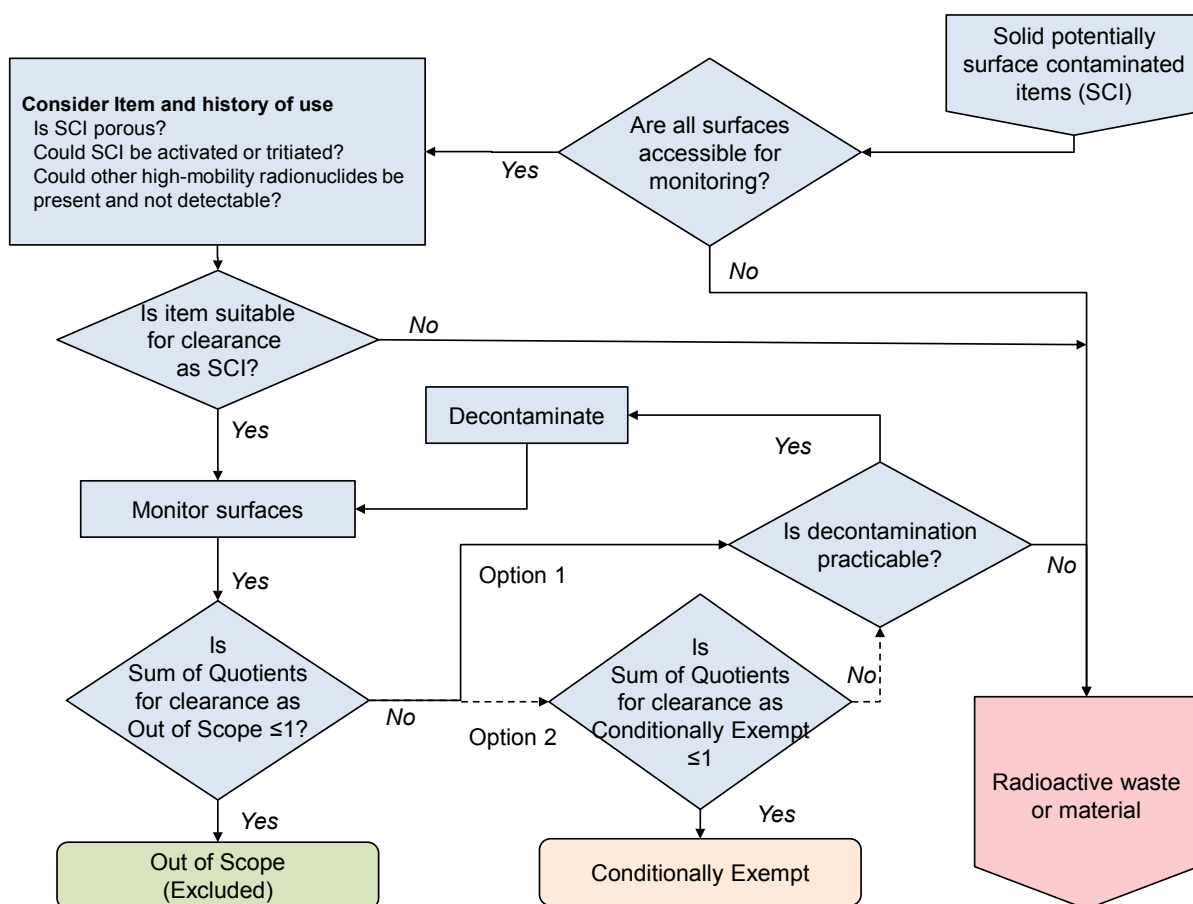
Notes: Option 1. Items that are not out of scope initially may be decontaminated and excluded subsequently.

Option 2. Items that are not out of scope may be conditionally exempt *only if they are not subject to an applicable permit*.

Wastes that cannot be demonstrated as out of scope or do not fall below the limits for conditional exemption, or fall within the remit of a permitted activity and are not eligible for conditional exemption should be sentenced as permitted radioactive waste. Materials that cannot be demonstrated as out of scope, or do not fall below the limits for conditional exemption may be subject to restrictions on movement or use. Secondary wastes generated (e.g. from decontamination) should be assessed as indicated in Figure 5.1.

5.13   If the item satisfies the criteria in para 5.12 for an SCI, derived surface clearance levels should be established as identified in Section 6.5. Surface samples or measurements should then be taken (for instance, this may be undertaken at a barrier associated with a controlled or supervised area under IRR 99 [1]).

5.14   Where practicable, surface monitoring is undertaken over 100% of surfaces but, where it is not, professional judgement should be used to decide adequacy and vulnerable areas for monitoring. In cases that are uncertain or complex, the process identified in Section 6.5 and Figure 5.6 (sentencing of potentially contaminated impervious solids) should be used. Guidance on measurement practices is presented in Chapter 7.

5.15   If contamination is found by monitoring, wipes should be taken at all locations where significant levels are found to determine whether the radioactivity is likely to be easily removable, and what fraction is fixed. If the fixed surface radioactivity exceeds any derived (justified) surface clearance levels the item cannot be sentenced as out of scope by this process, and must be considered under Section 6.5, according to circumstances.

5.16   If the fixed radioactivity is less than the derived surface clearance levels, the item should be decontaminated, and loose contamination removed as far as reasonably practicable. Following decontamination, surface monitoring should be undertaken again, especially on the previously contaminated areas. To confirm that any remaining contamination is not removable, wiping should be repeated. Further decontamination should be undertaken if necessary and if practicable.

5.17   The item is conditionally exempt if:

♦   the contamination is below the derived surface clearance levels; and,

♦   the calculated or measured total radioactivity on the surfaces, compared with the weight of the item (i.e. expressed as an activity concentration) does not exceed exemption limits.

5.18   Under all other circumstances, sentencing is undertaken according to the process outlined in Figure 5.6, which leads to other treatments being considered, or sentencing as radioactive and disposal in accordance with a permit where appropriate.

6.3   Sentencing of High Surface Area to Volume Items

5.19   Sentencing of high surface area to volume items and materials (in particular clothing and sheets of paper or plastic) should initially follow guidance presented in Section 5.2. Particular care should be taken to avoid contamination or activation of such items if clearance will subsequently be required. If this principle has been applied, such items and materials may be sentenced under Section 5.2.

5.20   Where it cannot reasonably be demonstrated by provenance that an item or material is clean, it must be sentenced as potentially radioactive.

5.21   If the item is physically a high surface area to volume item, but is potentially activated, or has had potential for contact with tritium or another diffusive radioelement such as caesium, it cannot be cleared as a surface contaminated item, but is sentenced following the procedures laid out in Section 5.4. Where the item is complex, or has inaccessible surfaces, Section 5.6 should be followed.

5.22   For all other potentially radioactive high volume to surface area items or materials, specialised bulk monitoring equipment (such as bag monitors) should be used, where practicable, to directly measure compliance with clearance and exemption limits (Figure 5.3). Surface monitoring and wiping are used to confirm that any enhanced areas and loose contamination comply with derived surface clearance levels established, as necessary, following guidance in Section 4.7. This process may be undertaken under a generic quality plan, often at a boundary (usually a barrier associated with a controlled or supervised area under IRR 99 [1]).

5.23 Where specialised bulk monitoring equipment, or suitable surface monitoring equipment which is capable of measuring compliance with clearance and exemption limits, is used the item or material may be classified as *excluded* if activity levels are below out of scope limits. Items or materials with higher levels of activity may be *conditionally exempt* or sentenced as radioactive.

If radioactivity is detected, wiping is required to determine whether it is removable. If decontamination is practicable, it should be undertaken as necessary and surfaces re-monitored.

5.24 Where surface monitoring is undertaken, the entire surface should be monitored on both sides if practicable and necessary. Where 100% surface monitoring is not undertaken, professional judgement should be used to include those areas most vulnerable to activation or contamination. Guidance on sampling and measurement (Sections 7) should be followed.

As examples where monitoring on both sides may not be necessary, clothes would normally only require monitoring on the outer surfaces of outer garments and some radioactivity on both sides of a thin item or material can be detected by monitoring one side only.

Figure 5.3 Clearance of High Surface Area to Volume Items (including Clothing) Using Specialised Bulk Monitoring Equipment able to Confirm Compliance with Clearance and Exemption Limits

Notes: Option 1. Items that are not out of scope initially may be decontaminated and excluded subsequently.

Option 2. Items that are not out of scope may be conditionally exempt *only if they are not subject to an applicable permit*.

Wastes which cannot be demonstrated as out of scope or which do not fall below the limits for conditional exemption, or which fall within the remit of a permitted activity and are not eligible for conditional exemption should be sentenced as permitted radioactive waste. Materials which cannot be demonstrated as out of scope or which do not fall below the limits for conditional exemption may be subject to restrictions on movement or use.

Secondary wastes generated (e.g. from decontamination) should be assessed as indicated in Figure 5.1

5.25   Specialised bulk monitoring equipment which is not sensitive enough to be able to confirm items or materials out of scope may be used if it has a limit of detection which is at least as low as the relevant exemption limits (within appropriate maximum missable activity limitations of the equipment), and the procedure outlined in Figure 5.4 should be followed for sentencing.

5.26   Maximum missable activity is defined further in Appendix G.

Figure 5.4   Clearance of High Surface Area to Volume Items (including Clothing) Using Bulk Monitoring Equipment or Surface Monitoring Equipment Unable to Confirm Compliance with Out of Scope Limits
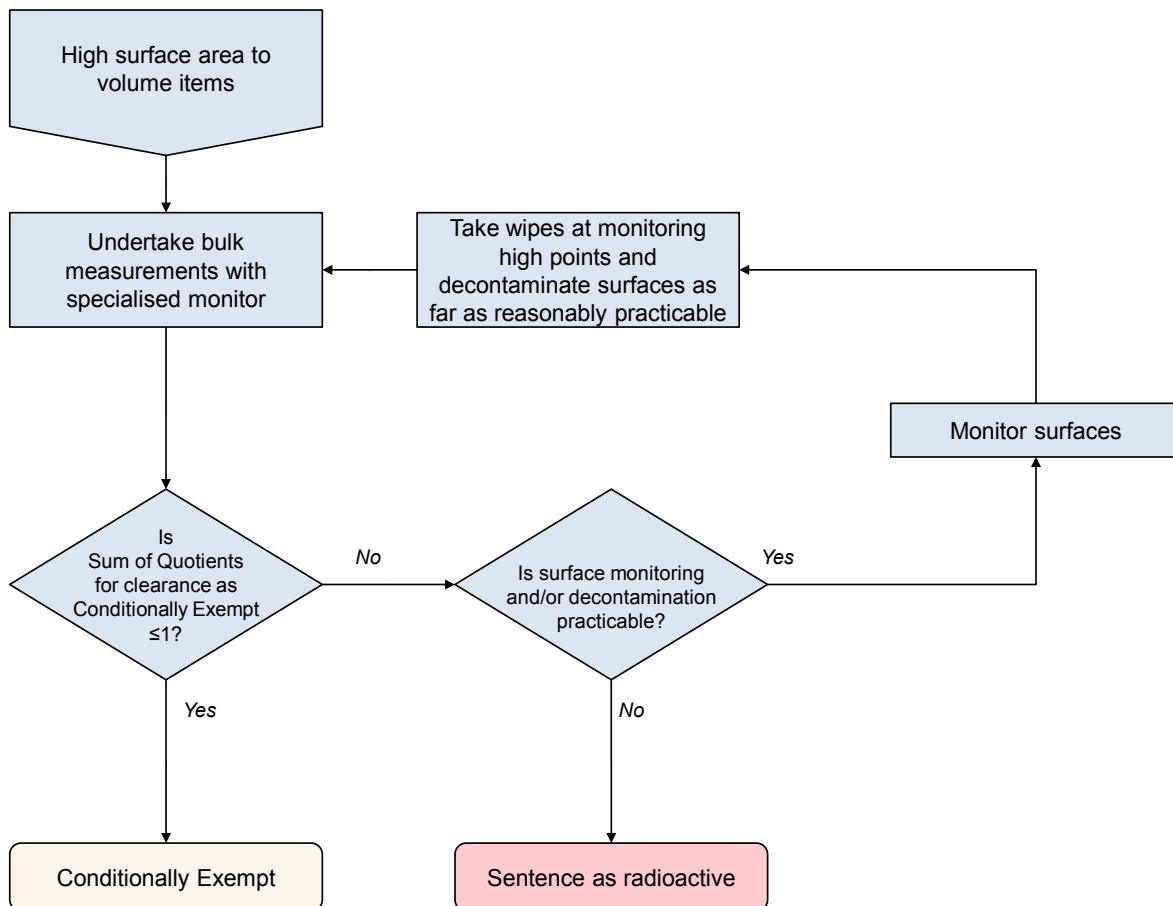
6.4   Sentencing of Potentially Activated or Tritiated Solids and Contaminated Loose or Porous Solids

5.27   Potentially activated or tritiated solids and contaminated loose or porous solids may be identified by provenance or by following the process identified in Section 4.1 for items or materials initially believed to be out of scope.

6.4.1 Potentially Activated Solids

5.28   Activation occurs in the bulk of the solid where neutrons have penetrated, and is strongly influenced by its elemental and isotopic composition. It can be highly variable in type, can be concentrated in certain parts of the solid and can be greater within the solid than close to its surface. If all the relevant irradiation and material parameters are known (neutron fluence, neutron distribution (beams or otherwise), neutron spectrum, elemental composition of the solid, activation cross-sections and decay parameters for the activation products and daughters) the radioactivity can and should be calculated or at least estimated. Most activation products are beta emitters (some are also gamma emitters, although these are not always penetrating radiations), so the capability of surface monitoring to measure them must be considered, and sampling within or coring into the solid may be necessary.

5.29   In circumstances where fissile contamination exists or has existed, fission products could also be present as well as activation products. These are assessed in the same way, although their physical distribution will be similar to that of the fissile parent.

5.30   From available data on irradiation history and existing or new screening monitoring, it will often be practicable to determine whether activation is likely to be close to or exceed relevant limits. At the same time the potential for the presence of surface contamination as well as activation should be considered. This may require measurement by a monitor which discriminates against radioactivity due to activation or by surface wiping and the levels compared with reference surface clearance levels.

6.4.2 Potentially Tritiated Solids

5.31   Tritium is a highly mobile in its HT form, and also as HTO, and, in evaluating the history of any solid potentially exposed to it, the following should be noted.

   i.   The form of the tritium at the time when exposure could have occurred is important.

   ii.   Surface contamination wipes are generally not sufficient as tritium may have permeated into the bulk volume and through seals and/or containment barriers.

   iii. The concentration of tritium may peak well below a surface where the outside surface was exposed to tritium but the exposure ceased some years ago.

   iv.   Absorption of tritium into the material will depend on a number of factors, such as the concentration, the form of tritium (elemental, oxide, particulate, liquid), the exposure period, humidity, pressure and temperature, as well as the form of the material.

   v.   For similar exposure histories, porous materials and items with a large moisture content, or hydrocarbon-based structure, for example: plastics, rubber, oils and greases, will have the highest absorption. Metals also absorb tritium to some extent, with the higher levels typically just below the surface.

   vi.   When surface contamination surveys are or have been undertaken, wipes taken immediately after cleaning of the surface can underestimate later contamination due to subsequent regrowth. Sufficient time between cleaning and surveys should be allowed.

   vii. Removable surface contamination does not necessarily correlate with volume absorption. Absence of surface contamination should not be taken to mean absence of bulk absorption; it may be necessary to take samples from within the solid.

5.32   Assessing tritium contamination from both history and measurement is highly specialised. However, tritium is very mobile and localised high levels within a material are not likely to be present, although high levels may be found within particular constituent materials with which tritium has particular affinity.

5.33   Note that tritium is now much less significant in terms of exclusion, as its level is now 100 Bq g^{-1}. It may now be possible to sentence material with only a relatively inaccurate knowledge of the tritium concentration.

6.4.3 Potentially Contaminated Loose Solids

5.34   For loose materials derived surface clearance levels have no significance. Knowledge of the history of the solid and how it could have become contaminated is very important to understanding the likely distribution profile of any radioactivity (e.g. if it is in particulate form, how large those particles might be). Screening using a suitable instrument capable of measuring hot-spots from the surface is often very useful (even if it is not capable of measuring down to uniform contamination at clearance or exemption limits), and such screening also indicates where some samples should be taken.

6.4.4 Potentially Contaminated Porous Solids

5.35   Knowledge of the history of the material and how it could have become contaminated are very important to understanding the likely distribution and nature of any radioactivity, whether it would have penetrated in liquid or gaseous form (e.g. elements that may form gaseous compounds formation of gaseous elements within a decay chain or diffusive radionuclides at elevated temperatures), or was in particulate form, and how large those particles might be. Screening using a suitable instrument capable of measuring enhanced radioactivity close to the surface (even if it is not capable of measuring bulk radioactivity within the solid) is likely to be useful, and also indicates where some samples should be taken.

5.36   For porous materials, assessment of activity concentration, the radionuclides present and surface activity levels is necessary to demonstrate compliance with exemption criteria and derived surface clearance levels in combination.   The activity concentration levels take precedence.

6.4.5 Sentencing

5.37   The sentencing process is summarised in Figure 5.5.

5.38   If activation, tritiation or contamination is estimated to be close to or greater than the relevant limits, the cost and practicability of further measurement or treatment has to be considered, and a decision taken whether the item or material should be sentenced as radioactive with minimal further measurement. In some cases, sentencing as radioactive may be the best practicable option if activation, tritiation or contamination is widespread and/or difficult to locate or segregate, but, if quantities are large, considerable effort to justify sentencing as out of scope or conditionally exempt may be appropriate. Furthermore, many activation products have relatively short half-lives and consideration should be given to whether the solid may decay to below relevant limits before it is sentenced. Tritium has a somewhat longer half-life of decay (of ca. 12.3 years) but consideration of radioactivity decay may also be appropriate before sentencing.

5.39   If levels of activation, tritiation or contamination are small, or efficient and effective treatment possibilities exist (these may include separation or segregation), a quality plan should be produced, which may be simple or very complex according to circumstances. The plan should define the chosen outcome of using all available information to consider all practicable treatment options, whether they satisfy BAT

and ALARP, their cost-effectiveness and the availability of destinations for the arisings. The plan should include the measurements required, how they will be assessed, and decision regimes.

5.40 Measurement methodologies must be very carefully chosen. Although screening by surface measurement may be useful, and passing material (crushed if necessary) under monitors on a conveyor may be sufficient for sentencing (depending on the penetrating properties of the radiation emitted by the contamination), sampling will often be required, and may be the only satisfactory measurement method for contamination by most alpha emitters. Samples should always be taken in locations where screening monitoring has indicated elevated levels as well as in locations indicated by statistical considerations. It is important that guidance on sampling, measurement and statistical analysis of data in Chapters 6 to 10 should be followed.

Figure 5.5 Sentencing of Potentially Activated or Tritiated Solids or Contaminated Loose or Porous Solids

Notes: Option 1. Items that are not out of scope initially may be decontaminated and excluded subsequently.

Option 2. Items that are not out of scope may be conditionally exempt *only if they are not subject to an applicable permit*.

Wastes which cannot be demonstrated as out of scope or which do not fall below the limits for conditional exemption, or which fall within the remit of a permitted activity and are not eligible for conditional exemption should be sentenced as permitted radioactive waste. Materials which cannot be demonstrated as out of scope or which do not fall below the limits for conditional exemption may be subject to restrictions on movement or use.

Secondary wastes generated (e.g. from decontamination) should be assessed as indicated in Figure 5.1

5.41   If a suitable process or treatment is identified, this should be described in detail in the quality plan and proposals for its implementation should be submitted to Company management, and/or the regulators informed, prior to undertaking it.

5.42   Arisings (which may include several or many sentencing volumes or segregated parts) are (individually) sentenced as out of scope if no radioactivity is detectable above out of scope levels, and there is adequate justification that none remains undetected. If radioactivity is detected, but is below Exemption levels and reference surface clearance levels (if relevant), they are sentenced as conditionally exempt. Additionally, if no radioactivity is detectable above out of scope levels, but there is insufficient justification that none remains undetected, the material should be sentenced as conditionally exempt. Further processing may be planned, approved and carried out for any arisings which are not sentenced as out of scope or conditionally exempt, or, if this is not cost effective or is unlikely to be successful, these arisings should be sentenced as radioactive.

5.43   If no suitable process can be identified which is likely to result in sentencing as *conditionally exempt* or *out of scope*, it may be best practice to sentence the item or material as radioactive.

6.5   Sentencing of Potentially Contaminated Impervious Solids

5.44   Contaminated or potentially contaminated impervious solids with accessible or inaccessible surfaces (which may include large or complex surface contaminated items such as metal transport flasks) may be identified by provenance or by following the process identified in Section 5.2 for items or materials initially believed to be out of scope.   Such solids must be sentenced using the process and procedures laid out in Figure 5.6, unless potentially activated or tritiated, in which case they are sentenced using the procedures laid out in Section 5.4 as appropriate.

5.45   For impervious solids with accessible or inaccessible surfaces, compliance with derived surface clearance levels are the principal practical criteria, but it will need to be demonstrated that compliance with these levels will ensure compliance with bulk activity concentration limits.   Knowledge of the history and use of the item (or material), and how it could have become contaminated, are very important to understanding the likely distribution of contamination on it and nature of any radioactivity. If it has had the potential to have been contaminated by a diffusive radionuclide such as caesium, which, like tritium, could have penetrated the surface, consideration has to be given to whether the radionuclide can be detected and the solid sentenced by surface measurement only; if not, Section 6.4.4 (for porous solids) should be followed.

5.46   If provenance and/or screening monitoring indicates contamination levels estimated to be close to or above the limits, the cost and practicability of further measurement or treatment has to be considered, and a decision taken whether the solid should be sentenced as radioactive without decontamination and with only minimal further measurement.

5.47   For impervious solids with accessible surfaces, both decontamination and surface monitoring will usually be practicable, although keeping worker doses ALARP and the contaminated secondary arisings likely to be created may both be important considerations.

5.48   For impervious solids with inaccessible surfaces, further measurements may present considerable difficulties, and dismantling of parts may be necessary in order to determine whether contamination is localised or whether decontamination of

component parts is practicable. For example, pipework potentially contaminated on inner surfaces may be cut into short lengths for monitoring and/or decontamination.

Figure 5.6   Sentencing of Potentially Contaminated Impervious Solids

Notes: Option 1. Items that are not out of scope initially may be decontaminated and excluded subsequently.

Option 2. Items that are not out of scope may be conditionally exempt *only if they are not subject to an applicable permit*.

Wastes which cannot be demonstrated as out of scope or which do not fall below the limits for conditional exemption, or which fall within the remit of a permitted activity and are not eligible for conditional exemption should be sentenced as permitted radioactive waste. Materials which cannot be demonstrated as out of scope or which do not fall below the limits for conditional exemption may be subject to restrictions on movement or use.

Secondary wastes generated (e.g. from decontamination) should be assessed as indicated in Figure 5.1

5.49   If contamination levels are mostly low, or efficient and effective treatment possibilities exist (these could include separation or segregation of parts), a quality plan should be produced, which may be simple or very complex according to circumstances. It is unlikely to be a completely generic plan, although surface monitoring is largely generic and the quality plan may incorporate a generic component such as monitoring of all locations (corners and crevices, and/or parts most likely to have been in contact with radioactivity) where contamination is most likely to be concentrated, and a sufficient fraction of the remaining surfaces. Additional methods of measurement, which may be useful in some circumstances, may include sampling of dirt in corners and crevices to determine whether it is

contaminated. Guidance on sampling, measurement and statistical analysis of data, presented in Chapters 6 to 10, should be followed.

5.50   The plan should also define the chosen outcome: using all available information to consider all practicable treatment options, whether they satisfy BAT and ALARP requirements, their cost-effectiveness and the availability of destinations for the arisings. It should include the measurements required, how they will be assessed, and decision regimes. The processes, including contingencies on finding elevated levels and decision criteria for consequential actions (if relevant), should be described in detail.

5.51   The plan should indicate the process to be followed if contamination is found by monitoring; usually wipes should be taken at all locations where significant levels are found to determine whether the radioactivity is likely to be removable, and what fraction is fixed. If the fixed radioactivity is less than the reference surface clearance levels, decontamination should take place, and loose contamination must be removed as far as reasonably practicable. Following decontamination, surface monitoring should be undertaken again, especially on the previously contaminated areas. To confirm that any remaining contamination is not removable, wiping should be repeated. Further (more aggressive) decontamination should be undertaken if necessary and if practicable.

5.52   Depending on the scale of potential contamination, proposals within the plan should be submitted to Company management and/or the regulators informed of them as necessary prior to undertaking it.

6.5.1   Determining excluded or conditionally exempt solids with accessible surfaces

5.53   If monitoring of any segregated part (if necessary) shows no detectable radioactivity above known normal background levels, and there is sufficient confidence that none could have been missed, then the item or part is excluded (*out of scope*).

5.54   If the contamination is below the derived surface clearance levels, and wipes (which measure loose contamination only) show no detectable radioactivity and the calculated or measured total radioactivity on the surfaces for the relevant item or part, compared with the weight of the item, does not exceed relevant limits, then the item or segregated parts are each conditionally exempt.

6.5.2   Determining excluded or conditionally exempt solids with inaccessible surfaces

5.55   Impervious solids with inaccessible surfaces present particular difficulties with respect to surface monitoring. If no significant levels of radioactivity are detected on exposed surfaces it may be possible to justify that the same will be true for inaccessible surfaces. However, for many items (such as an air intake or air filter) this would not be true and dismantling and segregation of the relevant component parts would be necessary. In all such cases, keeping worker doses ALARP and minimising any contaminated secondary arisings likely to be created are important considerations. It is important not to remobilise radioactive contamination.

5.56   Professional judgement is particularly important in these decisions.

6.6   Sentencing of Potentially Contaminated Liquids

5.57   All aqueous liquids (except 'relevant liquids', see below) and all gases (see Section 6.8) used in a practice are considered to be radioactive for the purposes of the

exemptions provisions legislation, irrespective of concentration (para 2.10 of the Government Guidance [9]).

5.58   Exemption provisions are made for very small quantities of aqueous radioactive waste (up to 100 Bq/ml to sewer) and for aqueous radioactive waste as excreta from patients undergoing treatment (e.g. subsequent to medical treatment with radionuclide labelled substances, and uranium/thorium aqueous liquids). These provisions are intended primarily for the non-nuclear sector, such as medical and educational facilities etc. They assume discharge to a relevant sewer (capacity >100m³ of effluent / day at the sewerage plant). They are therefore a 'special case' of aqueous waste disposals and are not considered further within this Good Practice Guide. However, it is noted that any person may use these provisions, provided that the conditions are met.

5.59   Exemptions provisions are also made for disposal of low concentration aqueous radioactive waste to sewer, river or sea. These provisions are intended primarily for those industries from which large quantities of aqueous effluent with low radionuclide concentrations are discharged to the environment. The exemption provisions do not apply if the premises from which the waste disposal takes place holds a permit for other aqueous radioactive waste streams.

5.60   Aqueous liquids containing suspensions of solids which are substantially insoluble, or immiscible non-aqueous liquids are analysed and sentenced following the process outlined in Figure 5.7*. All reasonably practicable measures must be taken to separate the liquid and solid phases.

5.61   For the purposes of the exemptions provisions legislation, aqueous liquid waste can include entrained solids or suspensions, provided that all practical measures have been used to attempt to remove such solid suspensions from the waste stream prior to disposal.

5.62   If the liquid is radioactive, it can only be discharged to water (sewers or controlled waters) if BAT (in England & Wales under EPR 2010) or BPM (in Scotland under RSA 93) has been applied to its treatment and if it is compliant with relevant permits or authorisations and non-radioactive properties specified by consents issued by Water Undertakings under the Water Industry Act (for sewers) or consents issued by EA or SEPA under the Water Resources Act (for controlled waters). These latter consents apply whether or not the liquid is radioactive, and constrain or prohibit the discharge of non-aqueous liquids.

6.6.1 The Meaning of 'Relevant Liquids'

5.63   The exemption provisions documents define a 'relevant liquid' as a non-aqueous liquid, and certain types of aqueous liquid with specified hazardous properties (see Section 2, paras 2.44-2.47 of [9]). The purpose of this definition is to allow such liquids to be treated, for the purposes of this legislation, as a solid because the exposure pathways are the same as those for solids.

5.64   For the purposes of waste disposal, the radiological impact assessments which support the clearance and exemption values are based on reasonable assumptions. For instance, the drinking water pathway giving rise to a human radiation dose is a

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*   This guidance is written primarily for aqueous liquids, since non-aqueous liquids (and other 'relevant liquids') may be treated as solids; see paras 5.63 to 5.66. Relevant liquids which contain largely insoluble sludges and/or suspensions of solids may be sentenced according to the guidance given here, if one or other phase is believed to be out of scope or other advantage is perceived for the separate sentencing of the liquid and solid phases. Alternative arrangements may be agreed locally with your regulator.

major feature of the assessment for aqueous liquids, but not for solids. Solids are not usually disposed of directly to rivers, and other legislation is intended to prevent such an activity.

5.65   There are certain liquids, for instance mercury and oils, for which the drinking water pathway equally can be ruled out, not least because other pollution control legislation does not allow disposals to the water environment.

5.66   Such liquids are to be compared with the exemption values derived for 'solids' and the disposal of such materials is to be to a conventional 'solid' waste route; that is, not disposed of to drains, sewers, open water or groundwater. A 'conventional' route includes disposal or transfer for the purposes of reuse or recycling.

5.67   There are certain aqueous liquids with specified hazardous properties which can likewise be treated as 'solids' (i.e. they are also 'relevant liquids'). A good example is hydrofluoric acid. Again, the drinking water pathway can be ruled out, not least because other pollution control legislation does not allow disposals to the water environment. In order to define this class of liquids, reference is made in the legislation to Council Regulation No. 1272/2008(1), which defines certain substances as being hazardous to health above specified concentration values. Aqueous liquids which exhibit acute toxicity, skin corrosion/irritation, or are acutely hazardous to the aquatic environment come within this class. Again, an assumption has been made that the disposal of such materials is to a conventional 'solid' waste route; that is, not disposed of to drains, sewers, open water or groundwater. A 'conventional' route includes disposal or transfer for the purposes of treatment, reuse or recycling.

6.6.2 Suspensions

5.68   If any solids are not substantially insoluble, it may be advantageous to consider either: i) chemical dissolution into a stable solution (and sentencing following the guidance presented in Section 6.6.3), or ii), more likely, chemical precipitation into a stable and substantially insoluble form (and then following the guidance in this section. These preliminary treatments are not considered in the Flowcharts.

5.69   If discharge of the aqueous liquid phase (including any solids which cannot reasonably be separated) is made under the exemptions provisions (i.e. it is treated as conditionally exempt) the waste disposal route can be to only one of a sewer or a watercourse (see para 3.166 of [9]). This means that in any calendar year, if any aqueous radioactive waste is disposed of to a sewer, then no waste can be disposed of under the exemption to a watercourse in that year. Likewise if waste is disposed of to a watercourse, then no radioactive disposals may be made in the same year to a sewer.

5.70   Within the exemption provisions documents, a watercourse is identified as a river, a tidal estuary or the sea. Discharges to static water (lakes, backwaters etc) are not exempt. Both watercourses and sewers are subject to minimum flow rates or capacities defined under the exemptions provisions as >1 m^3 per second for a river and a capacity >100 m^3 of effluent per day at the sewerage plant for disposal to a sewer*.

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*   A producer of aqueous radioactive waste will not know the precise flow rate of a river at any one time, and obviously has no control over how a sewerage plant is operated. However, if the waste producer is satisfied that these conditions have been met on first use of the exemption provisions, it can be assumed that these conditions will continue to be met unless information is received to indicate otherwise.

5.71   Discharges may also be made to a person who is permitted to receive such waste (for instance, via tanker).

5.72   It is important to note that the exemption provisions do not apply if the premises from which the waste disposal takes place holds a permit for other aqueous radioactive waste streams.

Figure 5.7   Sentencing of Potentially Contaminated Sludges or Suspensions
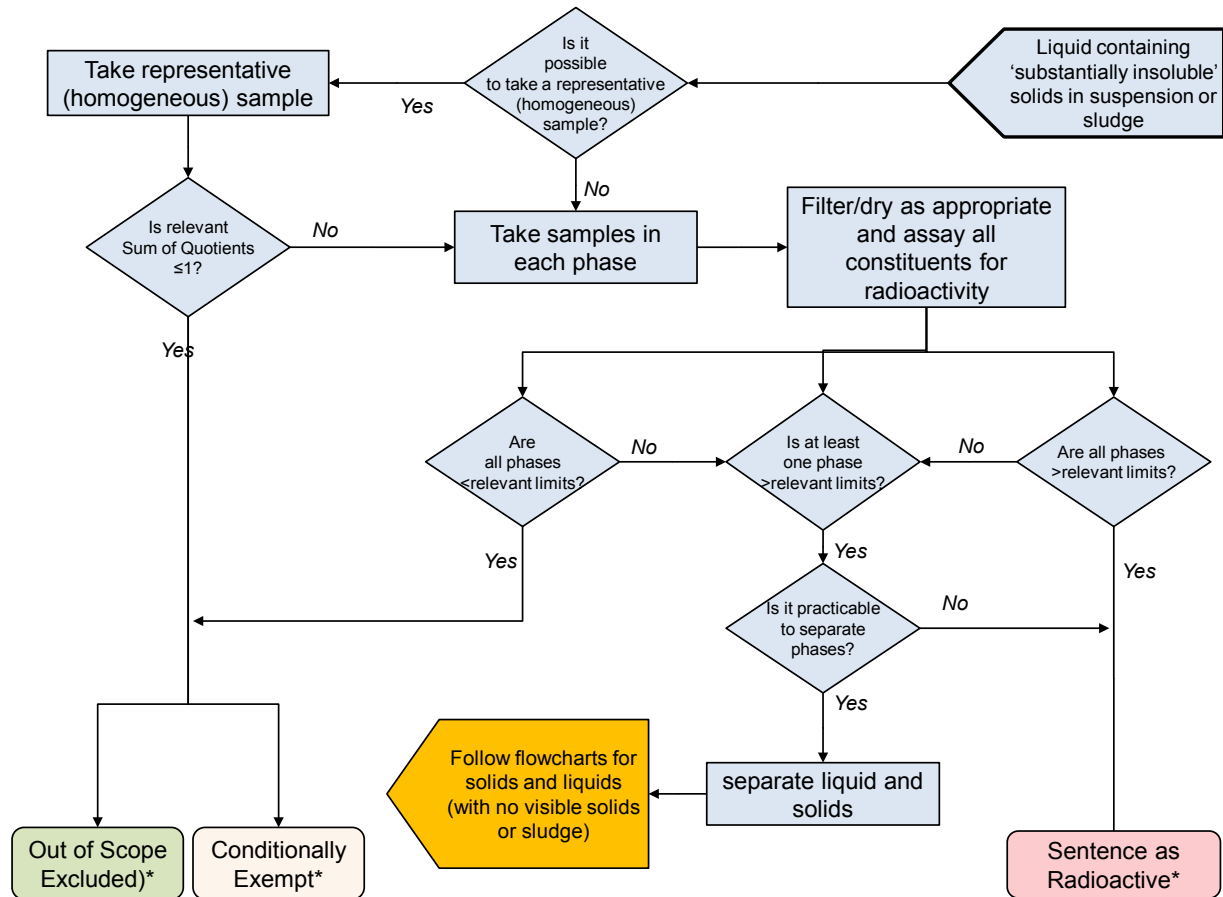
Notes: This flowchart is not intended for sentencing liquids which have not been used in a practice or activity which involves the radioactive, fertile or fissile properties of a substance.

Aqueous liquids used in a practice cannot be out of scope under the exemptions provisions documents. Aqueous liquids may be conditionally exempt *only if they are not subject to a permit*. Aqueous liquids (including liquids where separation of the liquid and solid phases is not practicable) which are above exemption limits or which are subject to a permit must be sentenced according to the flowchart presented in Figure 5.8.

Solids and non-aqueous liquids may be excluded, exempt or radioactive depending on activity concentrations and should be sentenced accordingly.

Where secondary arisings occur, these return to the start of guidance presented in Figure 5.1.

5.73   The flowchart outlined in Figure 5.7 should be used primarily to decide whether separation of the phases (or constituents) into liquids and solids would be worthwhile for waste management, re-use, recycling, recovery or disposal. The process assumes multiple constituents (e.g. immiscible liquids as well as suspended solids) although there will often be only one liquid and one solid phase.

Before disturbing any liquid of this nature, any additional risks it may pose should be considered, and any relevant clearances or authorisations to proceed must be obtained.

5.74   The exemptions provisions documents require that all reasonable measures are taken to separate out entrained solids or suspensions. If this is not practicable, a representative (homogeneous) sample should be taken. For liquid mixtures, it should usually be possible to stir quantities of up to about ten litres to achieve the uniformity required before taking a sample. For larger quantities, or if homogenisation is not practicable, samples should be taken in each undisturbed layer of liquid (if there are two or more immiscible liquid layers), and in the sludge.

5.75   Sampling of liquids should be consistent with sentencing volumes and several samples should be taken if inhomogeneity is suspected. In general, bulking of similar liquids from similar sources likely to have similar radioactive contents is permissible, and sentencing volumes are usually the same as storage volumes. However, the sizes of bulked quantities are often limited to relatively small amounts by handling practicalities.

5.76   Guidance on sampling, measurement and statistical analysis presented in Chapters 6 to 10 should be followed.

5.77   Liquid samples are filtered, if necessary, and both the liquid and dried filtered solids (suspensions) measured for radioactivity. If any method used drives off volatile substances which may be radioactive, these should be captured and also assessed (this possibility is unusual, and is not covered in the Flowchart). Determinations of whether the filtered liquid sample(s) (which could contain dissolved solids) would be radioactive or conditionally exempt are made following the guidance in Section 6.6.3. Determination of whether the dried solid component(s) would be radioactive, conditionally exempt or out of scope are made using the process outlined in Figure 6.5.

5.78   A liquid is conditionally exempt if radionuclides are present at below the specified limits (Table 3.4 of the Government Guidance).

5.79   If all phases are radioactive, there is likely to be no benefit in separating them unless this is necessary for disposal as radioactive wastes. If only some are radioactive, the practicability of separating some or all of them, and the benefits of sentencing separately the solid(s) and the liquid(s) should be considered. Decisions are likely to be based upon the availability of re-use, recycling, recovery or disposal routes for various mixtures and/or for their constituent phases.

5.80   It should be noted that liquid radioactive discharges to sewers or controlled waters are only permitted in compliance with authorisations issued under EPR 2010 [2, 3] / RSA 93 [4, 5], and their non-radioactive properties are limited by consents issued by Water Undertakings under the Water Industry Act [6, 7] (for sewers) or consents issued by EA or SEPA under the Water Resources Act [8] (for controlled waters). These consents apply whether or not the liquid is radioactive, and not only constrain or prohibit the discharge of non-aqueous liquids, but also the extent to which suspensions and sludges may accompany discharged liquids. Offsite disposal by specialist incineration is likely to be best practice for many non-aqueous liquids where this is permitted.

6.6.3   Liquids not Containing Visible Amounts of any Insoluble Solids

5.81   Aqueous and non-aqueous liquids which do not contain visible amounts of any insoluble solids are sentenced following the process outlined in Figure 5.8. Such liquids can arise, for example, from separation from sludges and/or suspensions (see previous section). Where solids are dissolved, it may be advantageous to precipitate them chemically (or evaporate a sample to dryness) and follow the process outlined previously (Section 6.6.2, Figure 5.7) to determine where any radioactivity resides. Alternatively, the liquid can be sentenced without separation from dissolved solids using the flowchart presented here.

5.82   In the case of dissolved solids in a non-aqueous liquid, the possibility that they may be precipitated in water may need to be considered.

5.83   While history and existing measurements may give a good indication of whether the liquid is *out of scope*, a representative sample should always be taken and analysed.   Small volumes should be stirred to ensure uniformity and a single sample taken; for larger volumes where stirring is not practicable, samples should be taken close to the top, middle and bottom, to detect unexpected non-uniformity. Bulking of similar liquids from similar sources likely to have similar radioactive contents is permissible, and sentencing volumes are usually the same as their storage volumes.

5.84   Sampling should be consistent with sentencing volumes, and sampling, measurement and statistical analysis of results should follow the guidance presented in Chapters 6 to 10.

5.85   Liquid samples should be measured without filtration or evaporation to ensure all radioactivity present is detected (liquid scintillation counting is likely to be most appropriate).

5.86   Any aqueous liquid (other than an aqueous liquid which is also a relevant liquid, see Section 6.6.1) used in a practice is in scope for the purposes of the exemptions provisions documents.   It is conditionally exempt if radioelements are present at below the specified limits (Table 3.4 of the Government Guidance).

5.87   A non-aqueous, or 'relevant liquid' is excluded (out of scope) or conditionally exempt if radionuclides are present at below the specified limits for solids (Tables 2.3 and Table 3.1, respectively, of the Government Guidance).

Figure 5.8   Sentencing of Potentially Contaminated Aqueous or Non-aqueous Liquids not Containing Visible Amounts of any Insoluble Solids
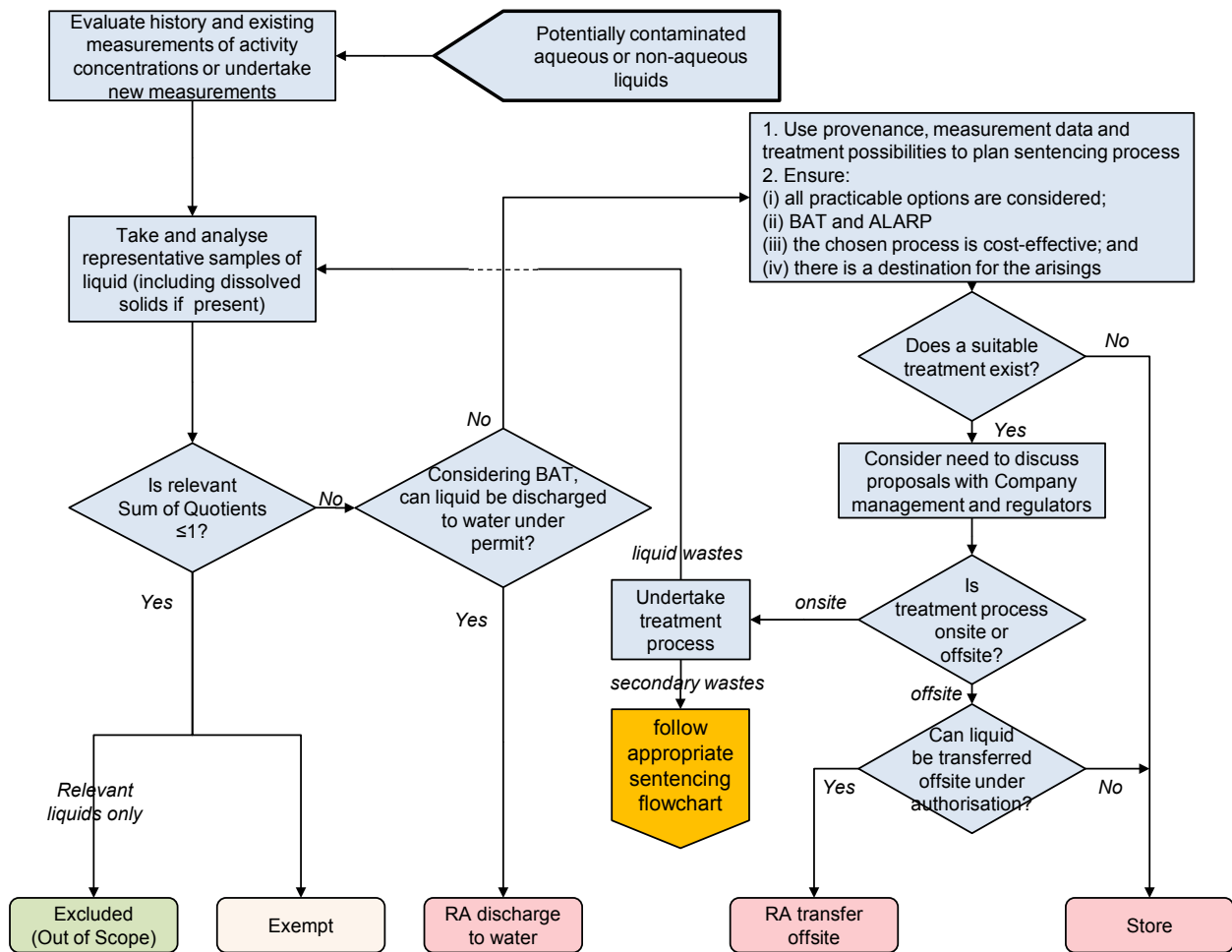
Notes: This flowchart is not intended for sentencing liquids which <u>have not been used</u> in a practice or activity which involves the radioactive, fertile or fissile properties of a substance. For sentencing of clean substances see Section 4.1.

Aqueous liquids used in a practice cannot be out of scope under the exemptions provisions documents. Aqueous liquids may be conditionally exempt *only if they are not subject to an applicable permit*.

Includes liquids which may contain very small amounts of solids and may be intended to be cleared for reuse, recycling or recovery as well as those to be sentenced for transfer or discharge.

Secondary or changed form wastes (e.g. solids) follow the appropriate flowchart.

6.7   Sentencing of Potentially Contaminated Sludges

5.88   Sludges may require special consideration as they are not necessarily categorised as 'liquids containing solids', since the dominant component may be the solid phase, but they generally contain levels of liquid in excess of those typically expected within a solid sample. In many circumstances, sludges should be dried and the solid component measured for radioactivity. Determination of whether the dried solid is radioactive, conditionally exempt or out of scope can then be made using the process outlined in Figure 6.5. However, if it is suspected that the process adopted for drying the sample will also drive off volatile substances that may be radioactive, these should be captured and assessed separately (this possibility is unusual, and is not covered in the Flowcharts presented here).

6.8   Sentencing of Potentially Contaminated Gases or Vapours (Including Aerosols)

5.89   All gases used in a practice or activity which involves the radioactive, fertile or fissile properties of a substance are considered to be radioactive material for the purposes of the exemptions provisions legislation, irrespective of concentration*.

5.90   If the gas or vapour is radioactive, it can only be discharged to air if BAT has been applied to its treatment (this will often require filtration where radioactive particulate may be present), and if it is compliant with relevant permits or authorisations and other regulatory constraints on the physical and chemical properties associated with discharges to air. These constraints apply whether or not the gas or vapour is radioactive, and are associated with permits issued by EA or SEPA.

5.91   Exemption provisions apply only to the situation where containers of liquids or solids are opened and the release of a small quantity of gas or vapour cannot be avoided. The exemption does not apply if the gas or vapour arises because a process (for example, deliberate heating) has been applied to the contained material. It does not cover any loss of gas or vapour after the liquid or solid has been dispensed.

5.92   There is an additional provision specifically for the case of the low radiotoxicity inert gas ^{85}Kr. Lighting devices which contain this radionuclide often undergo recycling procedures which result in release of the gas direct to atmosphere. Gaseous radioactive waste containing only ^{85}Kr as a radioactive component up to an annual total activity released of $1x10^{11}$ Bq is exempt.

5.93   Most radioactive gaseous discharges are associated with ventilation of buildings, and consist of air potentially containing radioactive gases and aerosol particulates. Air is continuously discharged, often through filtration plant with online sampling and/or monitoring. Continuous discharge processes of this type are not within the scope of this Good Practice Guide.

Government Guidance [9] requires that, to the extent that it is reasonably practicable, in respect of gaseous radioactive waste which arises in a building, the waste is to be disposed of by an extraction system which removes the waste from the area where it arose and which vents the waste into the atmosphere; and prevents the entry or the re-entry, of the gaseous radioactive waste into a building.

5.94   Gases or vapours may contain solid particulates or liquids in aerosol form. Provided that all practical measures have been used to attempt to fully remove such solid and liquid components from the gaseous waste stream, such particulates or aerosols may be treated as an integral part of the gaseous waste stream.

5.95   Gases or vapours which are used in, or arise from, industrial activities and where naturally occurring radionuclides are present below activity concentrations identified in Column 4 of Table 2.2 of the Government Guidance [9], and where the process or activity is independent of the radioactive, fertile or fissile properties are conditionally exempt (cf. para 5.89). Naturally occurring radionuclides that are not listed in Table 2.2 of the Government Guidance are out of scope of the exemption provisions legislation. This includes, for example, potassium-40 (^{40}K).

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*   Gases or vapours which contain only radionuclides having half-lives of less than 100 seconds, and whose decay products also have half-lives less than 100 seconds (para 2.31 of [9]), or where no radioactivity is positively detectable above known normal background levels (para 2.4, 2.8, 2.18 of [9]), are out of scope. **For radioactivity to be "not positively detectable" BAT should be applied.   Detection limits should be assessed and their adequacy justified as necessary.**

5.96   Gases or vapours which are used in, or arise from, industrial activities and where naturally occurring radionuclides are present above activity concentrations identified in Column 4 of Table 2.2 of the Government Guidance [9] are radioactive and not exempt.

5.97   Contaminated or potentially contaminated gases or vapours are sentenced following the procedure outlined in Figure 5.9.

Figure 5.9   Sentencing of Potentially Contaminated Gases or Vapours
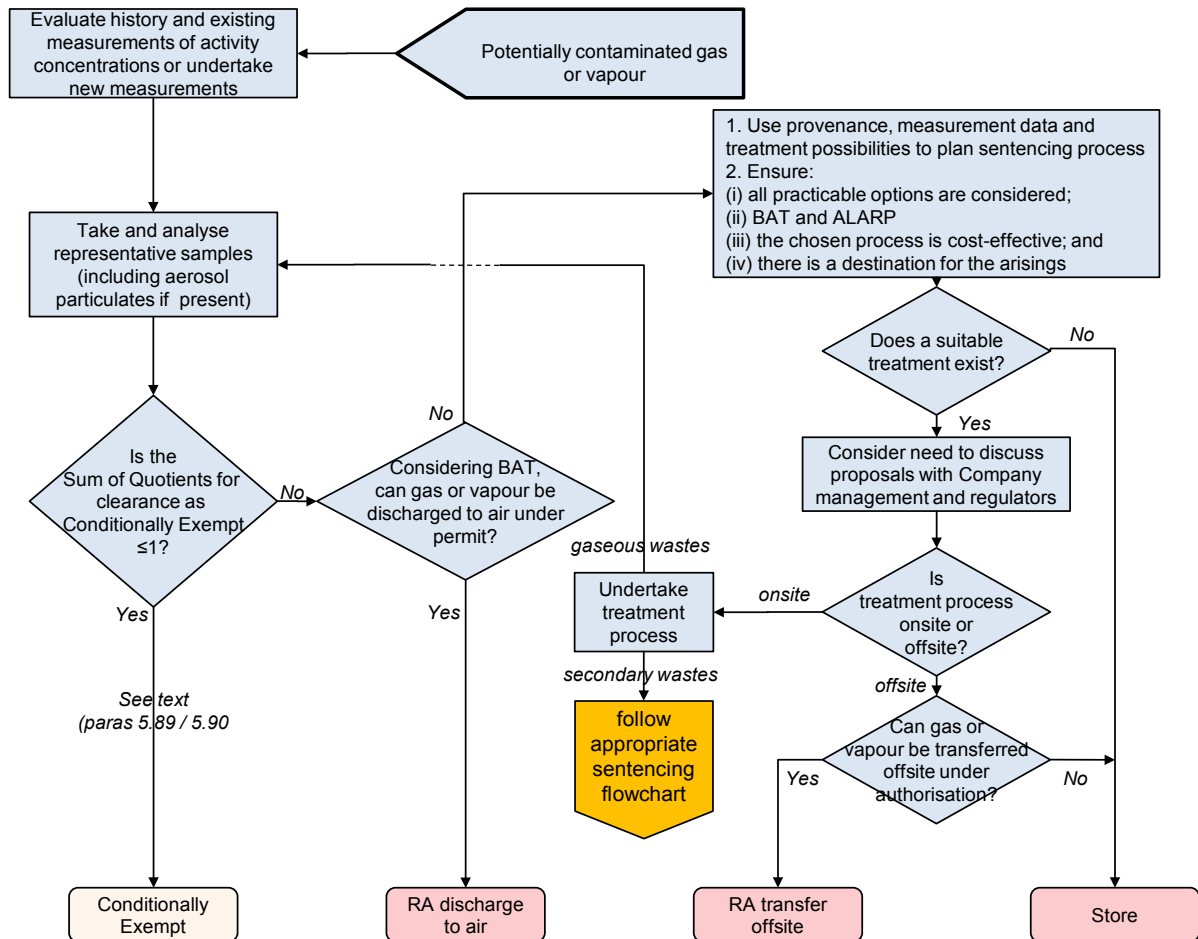
Notes: This flowchart is not intended for sentencing gases which have not been used in a practice or activity which involves the radioactive, fertile or fissile properties of a substance. For sentencing of clean substances see Section 4.1.

Gases used in a practice cannot be out of scope under the exemptions provisions documents.

Includes gases and vapours which may contain aerosol particulate and may be intended to be cleared for reuse, recycling or recovery as well as those to be sentenced for transfer or discharge.

Secondary or changed form wastes (e.g. adsorption or chemical fixing producing solids) should be sentenced following the appropriate flowchart.

Exemption provisions do not apply where the discharges are subject to a permit.

5.98   History and existing measurements provide information on the potential activation or contamination levels. Measurement by external (gamma) monitoring or internal monitoring (passing the gas or vapour itself through an ionisation or proportional counter) may be applicable. In some cases physical or chemical entrapment of the radioactivity from a sample of the gas (such as filtration of air containing potentially radioactive aerosol particulate, or capture of tritiated water in a bubbler) may be appropriate. Guidance in Section 7 should be followed.

5.99   If discharge is not permitted, further treatment should be considered. This will require a quality plan to be produced, which may be simple or complex according to circumstances. The plan should define the chosen outcome of using all available information to consider all practicable treatment options (including both onsite and offsite treatments), whether they satisfy BAT and ALARP, their cost effectiveness and the availability of destinations for the arisings.

5.100   If treatment onsite is the best option, the plan should include the measurements required, how they will be assessed, and decision regimes. Measurement practices should use guidance in Section 6. If treatment is to be undertaken offsite, much less detail may be necessary in the quality plan. If no suitable treatment can be identified which is likely to result in a route for disposal for arisings, it may be necessary to store them until one is available.

5.101   If a suitable treatment is identified, this is described in the quality plan, and proposals should be submitted to Company management and/or the regulators informed of them as necessary prior to undertaking it. For treatments undertaken onsite, gaseous arisings are re-measured after treatment against the same criteria as before; radioactive solid arisings (following chemical fixing for example) will follow appropriate disposal procedures. For treatments to be undertaken offsite, authorised transfer is required. If this is not available, the arisings will have to be stored onsite until an authorisation is obtained.

6.9   References

1   The Ionising Radiations Regulations 1999. Statutory Instrument 1999 No. 3232. The Stationery Office. Available from:
        http://www.legislation.gov.uk/uksi/1999/3232/contents/made

2   Environmental Protection, England and Wales. The Environmental Permitting (England and Wales) Regulations 2010. Statutory Instrument 675. The Stationery Office. Available from http://www.legislation.gov.uk/uksi/2010/675/contents/made

3   Environmental Permitting (England and Wales) (Amendment) Regulations 2011. Statutory Instrument 2043. The Stationery Office. Available from http://www.legislation.gov.uk/uksi/2011/2043/contents/made

4   Radioactive Substances Act 1993. The Stationery Office. Available from http://www.legislation.gov.uk/ukpga/1993/12/pdfs/ukpga_19930012_en.pdf

5   The Radioactive Substances Exemption (Scotland) Order 2011. Statutory Instrument 147. The Stationery Office. Available from http://www.legislation.gov.uk/ssi/2011/147/contents/made

6   Water Industry Act 1991 (as principally amended by the Water Industry Act 1999 and the Water Act 2003). Available from:
        http://www.legislation.gov.uk/ukpga/1999/9/pdfs/ukpga_19990009_en.pdf

7   Water Industry (Scotland) Act 2002. http://www.legislation.gov.uk/asp/2002/3/contents

8   The Water Resources Act 1991 (as principally amended by the Water Act 2003).
        http://www.legislation.gov.uk/ukpga/1991/57/contents

9   Guidance on the scope of and exemptions from the radioactive substances legislation in the UK. V 1.0 Sept 2011. Llywodraeth Cymru, DoENI, Scottish Government, DECC, DEFRA. http://www.defra.gov.uk/publications/files/pb13624-rsl-guidance-110914.pdf

7   Measurement Practices

7.1   Principles of Monitoring

6.1   This Chapter provides information on the basic processes and techniques of monitoring. Figure 6.1 and Figure 6.2 summarise the process to be used when considering the monitoring approach techniques that are appropriate.

6.2   The purpose of monitoring and sampling is to produce a numerical estimate of surface or bulk activity levels which can be compared with criteria described elsewhere in this document. Often, because of the uncertainties in the process and the fact that many of the materials monitored may be genuinely clean, the results will demonstrate that the materials under investigation are below the minimum reliably detectable (or maximum missable) activity (MMA).

6.3   The methods used for this and the equipment employed will depend on:

♦   the physical form of the materials to be monitored,

♦   the relevant averaging areas and masses,

♦   the natural background levels in the materials,

♦   the fingerprint, i.e. the expected contaminating radionuclide mix,

♦   the desired maximum missable activity,

♦   the fraction of any material close to the exclusion or exemption level,

♦   the environment in which the monitoring is to take place,

♦   the type of person who is going to perform the measurements,

♦   when the monitoring is to take place, and

♦   the balance between manual and automatic monitoring.

6.4   These points will be expanded on later in this chapter. Frequently, deciding on exactly the method of monitoring will be an iterative process, where a variety of techniques and equipment is considered, the pros and cons weighed and a judgement made on what is the best approach for the particular circumstances.

7.1.1   The physical form of the materials to be monitored

6.5   Chapter 6 comprises a set of flow charts which are to be used in the assessment of bulk and surface activity and which are based on the physical form of the material to be cleared. The influence of the physical form of the materials to be monitored is considerable. Intact solids such as steel plate and bricks demand sampling methods which are aggressive for bulk samples, but are easy to monitor directly for surface contamination. Materials such as wire, piping and cable can be cut up into convenient sized pieces for bulk activity assessment. However, for many materials, direct contamination monitoring is difficult and wiping may be unacceptable because of safety considerations.

6.6   For contamination monitoring, surface condition can also be important. Direct monitoring of low range emissions such as soft betas and all alphas can only take place on surfaces that are essentially clean in terms of dust, grime and grease and are free of condensation. If activity could be buried beneath a layer of grease or paint then that surface is unmonitorable. In addition, for low range emissions, surfaces need to be relatively flat so that the distance between detector and surface does not vary by more than a few mm over the area of the detector window. Direct counting of wipes from a greasy surface is also impossible, as any grease will greatly reduce the counting efficiency of any detector. Such wipes will require

counting by liquid scintillation or will require radiochemical treatment to produce a countable sample. In effect, only surfaces which are clean and dry and where there is no chance of significant activity under paint are acceptable for direct monitoring for low range radiations. This means that many surfaces which may have been contaminated at some time will have to be cleaned down to the earliest surface before monitoring.

6.7   For each material anticipated, a careful assessment of the physical form will be essential to allow selection of the most appropriate general method, monitoring device type and monitor size.

6.8   Detailed description of the monitoring techniques is given in Appendix C.

Figure 6.1   Overall Process for use when Considering the Approach to Monitoring (Part 1)
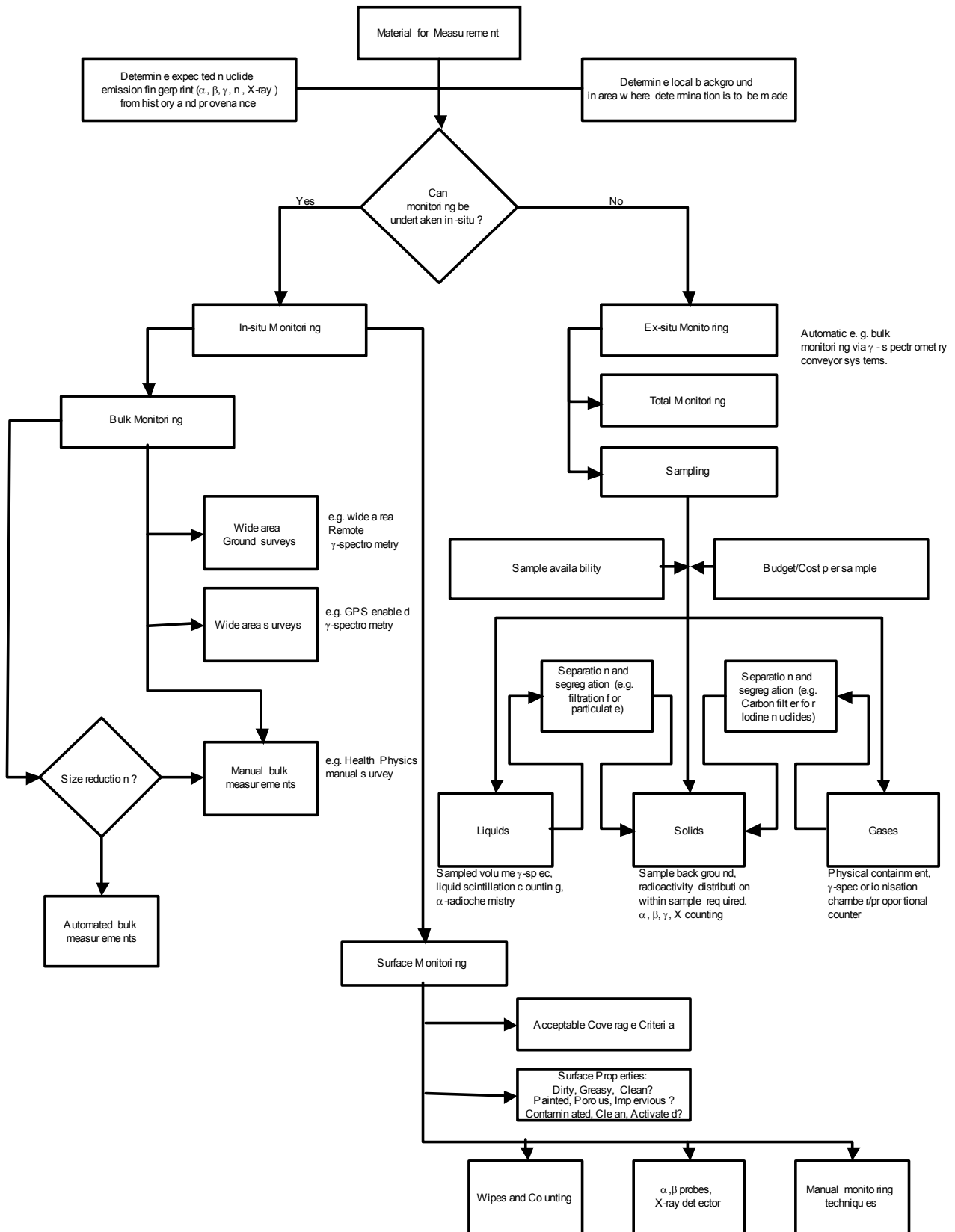
Figure 6.2   Overall Process for use when considering the Approach to Monitoring (Part 2)
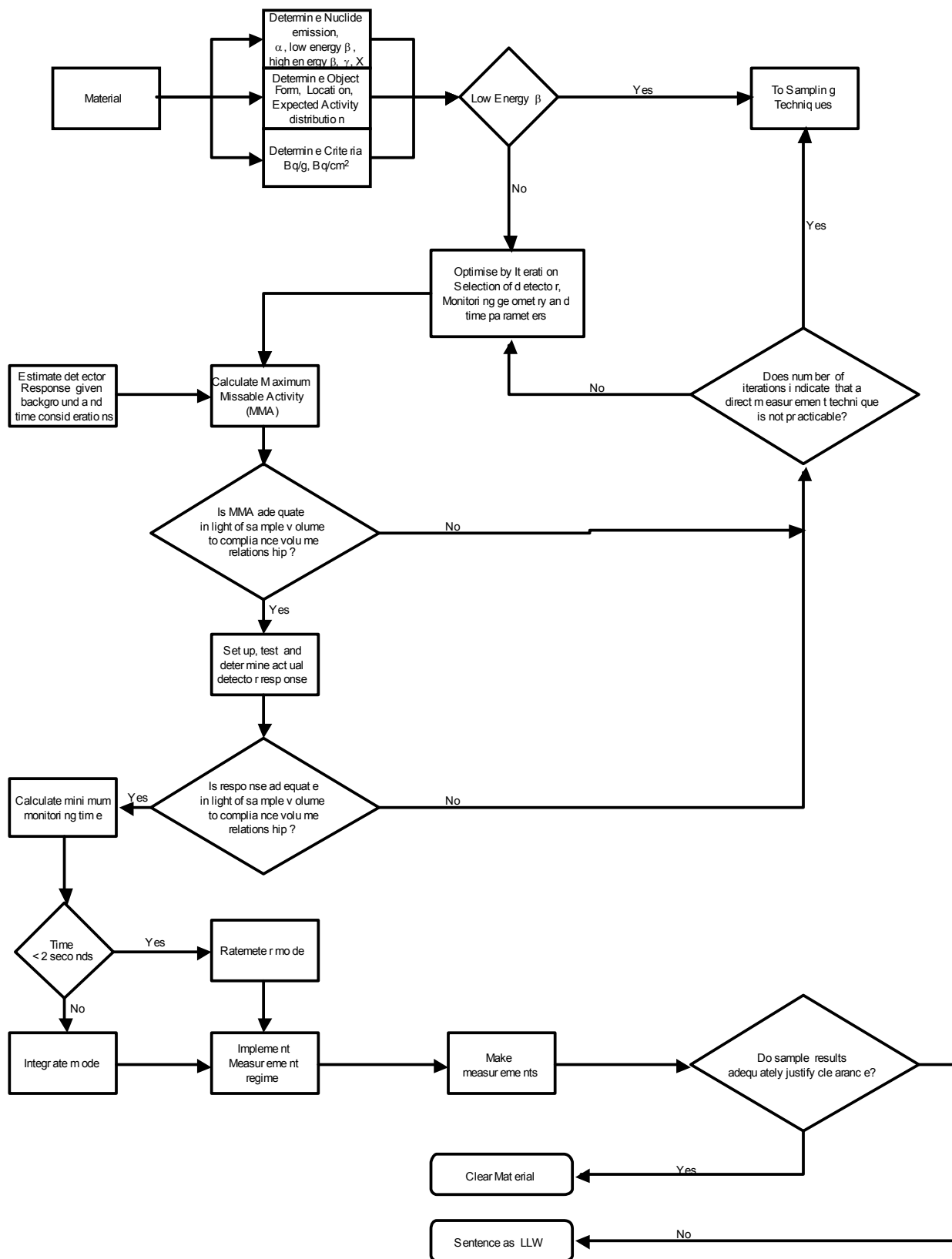
7.1.2 Permitted Averaging Areas and Masses

6.9   Averaging volumes for sentencing are discussed in Section 4.5. Averaging areas for sentencing are laid out in ISO 7503 Part 1*.

6.10   The form of the material may define the maximum effective area of the monitoring device, particularly for direct surface contamination monitoring. As an example, the choice of equipment available for monitoring for beta activity inside a pipe is likely to be limited. However, for bulk activity assessment, the user is likely to be able to obtain equipment in a range of sizes.

6.11   For direct surface contamination monitoring, the time taken to monitor a particular area to a particular level of confidence is inversely dependent on approximately the square of the detector size. Hence, doubling the detector size will tend to reduce the time taken to monitor a particular area by a factor approaching 4. There are 2 influences. One is obvious, in that the number of measurement points or detector repositionings required is inversely proportional to the detector size. The other, less obvious, one is that the length of time required to accumulate a statistically acceptable number of counts is generally proportional to the inverse of the detector size. The same general effect occurs for volume sources and bulk activity assessment.

6.12   Hence, it is advantageous to make use of the maximum practicable and permitted areas or volumes when designing the monitoring regime.

7.1.3 Natural Background Levels

6.13   All practical materials have some natural radioactive content and, in many, the radioactive content approaches or exceeds 1 Bq g^{-1}. This natural level makes the detection and measurement of any possible added activity more difficult to perform. One very common example is a high level of potassium in some types of high quality brick. All potassium contains the isotope ^{40}K, which emits energetic gamma radiation (1.46 MeV). If the potential contaminant is ^{137}Cs (0.662 MeV gamma) then there will always be some interference by the ^{40}K with the ^{137}Cs measurement, because Compton scatter within the bulk material will generate a number of 0.662 MeV gammas. The same problem affects tiles and glazed sanitary ware. Plasterboard can sometimes contain significant levels of ^{226}Ra that will be in equilibrium with its decay chain down to ^{214}Po. This decay chain generates a complicated mixture of alpha, beta and gamma radiation.

6.14   The influence of the natural activity can be minimised by using energy selective monitoring, discussed later in detail for gamma radiation but also applicable to beta radiation. In cases where the natural level is constant, the main effect is that the background count rate from any monitoring equipment is increased, which increases the statistical uncertainty in any measurement of net activity. A more significant problem is where it is variable, as might be the case when demolishing a building that uses 2 types of brick. The background in that case could well depend on the mix of the two types in any load. This will further increase the uncertainty. This may best be managed by ensuring that loads are segregated so that the problem does not occur. A further similar complication can arise with tiled areas in buildings. Tiles can have very high levels of bulk activity and are difficult to separate from walls.

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*   ISO 7503-1:1988. Evaluation of surface contamination -- Part 1: Beta-emitters (maximum beta energy greater than 0,15 MeV) and alpha-emitters.

6.15   Hence it is vital that the natural nuclides present in any material are identified and measured before choosing monitoring techniques and equipment and before planning the demolition sequence.

7.1.4   The Fingerprint

6.16   In the same way that it is essential to understand the natural activity in a material then it is essential to understand the expected contaminating nuclide mix, i.e. the fingerprint.

6.17   The aim should be to subdivide any task into a series of areas where it is possible to be confident that the nuclides present are in relatively fixed proportions. This concept is fundamental to the application of zoning, as discussed in the previous chapter. The fingerprint can sometimes be easy to decide. If an area has only processed one nuclide which has a long half-life and no significant progeny then the fingerprint is that nuclide. However, if there is the potential for a complicated mix of nuclides to be present then deciding on the fingerprint can be much more difficult. It is essential that sufficient time, thought and money are devoted to producing each fingerprint as mistakes can lead to delay, expense and loss of credibility later. One problem that can arise is where there is a potential mix of fuel, fission products and activation products. Within that mix, there are gamma emitters, alpha emitters, relatively easy to monitor beta emitters, low energy beta emitters, low energy X-ray emitters and tritium.

6.18   Tritium has been identified separately because its chemical and physical properties are very different to most other nuclides, particularly its high mobility.

6.19   Fingerprinting will normally demand sampling which should be guided by an understanding of the process that took place and by direct measurement. For example, for soil contaminated by fission products, ^{137}Cs is likely to be present. The highest activity concentrations can be identified using a large sodium iodide scintillation detector. Samples can be taken and counted by gamma spectrometry to assess the activity of the ^{137}Cs and other gamma emitters. This should then be followed by radiochemistry to assess the activity of the other nuclides likely to be present, such as ^{90}Sr + ^{90}Y, which are difficult to monitor directly. Similarly, where the material under consideration is steel which has potentially been activated, there are several computing codes that can be used to predict nuclide levels based on knowledge of the alloy and the neutron spectrum and intensity. These levels should then be corrected for radioactive decay to give a current predicted nuclide mix.

6.20   For direct monitoring to be possible there must be at least one directly measurable nuclide present in relatively fixed proportions to the others. Activity estimation can then go ahead on the basis of monitoring for that nuclide and deriving a maximum acceptable count rate, for example, which takes account of the fraction of the fingerprint which is detectable and the limiting activity level. Direct monitoring per square meter of surface typically costs less than 1% of the cost of analysing a single sample.

6.21   Even if apparently stable fingerprints are found, it is important to repeat the process as clearance takes place. Physical and chemical effects can change the nuclide ratios in soil, for example, where ^{137}Cs, ^{90}Sr and ^{90}Y can have different mobilities. There may be direct ways of checking this, such as the gross beta to ^{137}Cs ratio or the count rate ratio from a beta detector fitted with energy windows, which are either not too expensive or can be performed in situ, but it may also be necessary to repeat the full radiochemical investigation from time to time.

6.22   This process will allow selection of the best monitoring method and equipment and the calculation of responses per Bq.cm^{-2} or Bq.g^{-1} as appropriate, using information

from type test data. It may also influence other aspects of the clearance process, such as the segregation of different materials.

7.1.5   Identification of the Desired Maximum Missable Activity

6.23   The desired maximum missable activity is fundamental to the selection of monitoring technique and equipment (see Appendix B for more detailed information on the meaning and application of Maximum Missable Activity).

6.24   It is important that the final technique should be capable of identifying a sample at exactly the sentencing limit on 95% of occasions as being potentially at, or in excess of, the limit.   It is also important that the technique does not yield an excessive number of false positives, which is when it rejects material that is in fact significantly below the sentencing limit. For many circumstances, selection of the technique should be an iterative process, where the total costs (time, equipment, services, and staff costs) are balanced against the technical quality of the process. The final selection is a technique that will produce a result of the desired quality but at the lowest cost.

7.2   The fraction of any material close to the exemption level

6.25   Where the monitoring process is expected to be a formality, i.e. the material is probably either clean or very lightly contaminated, then quite simple instrumentation can often be used, provided that the chance of a false positive or negative is small. This might apply to surface contamination of a thick impervious material by an energetic beta emitter, for example. In that case, any large area beta probe will suffice.

6.26   For situations where a significant fraction of the material is expected to be close to the exemption level then it is probably cost effective to use more sophisticated equipment which produces a lower level of uncertainty at the clearance level. This might use mechanical filtering or some degree of spectrometry, for example. Alternatively, it might be possible to first survey the material with a quick technique and then resurvey the fraction where it is not possible (on the basis of the quick measurement) to decide confidently whether it is conditionally exempt or above the limit. The re-survey could use the same equipment but a longer counting time to reduce the statistical uncertainty.

7.2.1   The Environment in which the Monitoring is to take Place

6.27   The environment in which the monitoring is to take place is very important. The better the environment for equipment and staff, the better will be the quality of the result and the higher the throughput. The most difficult environment is the one that is changing.

6.28   Generally, monitoring in buildings which are being stripped is difficult. Lighting, ventilation and cleanliness can all be less than satisfactory. The possibility of cross-contamination of cleared materials has to be avoided. Any materials which are found to exceed a limit should be segregated away from cleared materials. Normally, it should be very rare to find activity significantly over the set limit during the clearance process as all such items should have been identified and either cleaned or removed earlier.

6.29   For surface contamination monitoring, complete access to the surfaces of interest is essential (see Figure 5.2). Sometimes it is unlikely that activity is present inside gas cylinders, for example, and only the outside would require monitoring. This would apply to cylinders of counting gas for hand and foot monitors, for example.

Conversely, cylinders used as part of an active gas process could well be internally contaminated and would require the assessment of internal and external activity.

6.30   It is important that a person performing monitoring is comfortable. Equipment should be designed or adapted to ensure this. For small objects, a well-lit stainless steel surfaced sorting table is ideal. For larger objects and for in situ monitoring of equipment floor monitors are often ideal. These have wheels which can be used to keep a fixed surface to detector sensitive volume distance. This is particularly important where the emissions are alpha and soft betas and the count rate is very dependent on distance.

6.31   Environmental background stability is also paramount. There is no point trying to perform monitoring at release levels for bulk gamma emitters, for example, where site operations such as the movement of waste packages in an adjacent building is taking place. Similarly, where the material to be monitored for release is moveable, the pros and cons of moving it to a central monitoring station in a low background building (rather than working in a normal or variable background building) should be assessed.

7.2.2 Who Performs the Measurements?

6.32   Clearance monitoring is very different from routine radiation protection monitoring, mainly because acceptable residual levels are generally less than normal operating limits and are often close to the minimum reliably detectable level. In establishing a clearance monitoring programme consideration should be given as to the benefits or otherwise of using radiation protection monitoring staff or training new staff. The new people come with a fresh mind, whereas established staff sometimes find it difficult to appreciate the importance of complying with clearance levels. Against this, established staff can bring knowledge of the likely areas of maximum contamination in equipment and materials removed from an area in which they had worked.

6.33   There is a very clear trade-off between staff skill level and equipment capability. The less the staff skill, the greater the reliance that is placed on the equipment. Clear thought on these points will help the development of a robust monitoring programme greatly.

7.2.3 When to Perform the Monitoring

6.34   **The timing of monitoring is not a trivial consideration.** Monitoring early in any demolition process or strip out runs the risk of the material being contaminated by dust from other parts of the site. Monitoring after removal means that the object will have been handled and any activity may have been transferred on to workers and cutting equipment. Monitoring after demolition means that surfaces have been broken up and aren't accessible and volumes of significant activity may have been buried under relatively clean material or may have been mixed in with clean material, greatly increasing the volume of active waste.

6.35   Generally, the best approach is to have a good understanding of the problems, supported by *in situ* monitoring information, and then plan the clearance process to ensure that potential cross contamination is minimised. Where equipment, such as benches, is to be left, then the last step should be monitoring to confirm that the article meets the set criteria. Similarly, for a building, the contents should be removed and then the building monitored before demolition.

7.2.4 The Balance between Automatic and Manual Monitoring

6.36   An automatic process is far better for clearance operations which require a large number of repetitive measurements. It is auditable and its performance is easier to

predict. A machine does not get bored. Clearance monitoring is generally a rather dull process where virtually all the results are so close to background as to be indistinguishable. The end result can be that the quality of monitoring declines catastrophically and, eventually, a significantly contaminated item slips through the net.

Automatic monitoring is preferable where both technically possible and financially viable.

7.2.5   Reaction to Unexpected Results and Management Control

6.37   By the time monitoring for release begins, the operator should have a sufficient knowledge of the area, processes and plant to have removed anything that is not expected to meet the release criteria. Even when material has been sentenced, it often makes sense to pass some types of waste, such as scrap steel, through a gate monitor designed for scrap monitoring. This will pick up radioactive objects in the scrap which have got there either by error on the part of staff or because of an unexpected change in circumstances.

6.38   If anything unexpected does happen, it is essential that the management investigate the circumstances in sufficient detail to identify why it happened and to develop procedures to reduce greatly the chance of it happening again. This could involve reviewing the zoning of areas, for example, or developing a deeper understanding of the work that took place in the area which is being stripped.

7.3   Monitoring Equipment

6.39   Typical monitoring equipment is described in detail in the appendices. It can be subdivided into 2 broad categories, bulk and surface monitoring. In the first category, the measurement quantity of interest is generally activity per unit mass (Bq g^{-1}) whereas in the second it is activity per unit area (Bq cm^{-2}). Activity per unit mass is the quantity of interest when demonstrating compliance with release criteria. Activity per unit area can be used to calculate activity per unit mass for surface contaminated objects and to demonstrate compliance with transport limits.

6.40   Surface contamination monitoring is generally concerned with the estimation of alpha and beta activity, but there can be circumstances where the main contaminant is an X-ray emitter such as ^{55}Fe. Generally, direct monitoring for high energy gamma emitters for surface contamination assessment is best avoided. Normally such nuclides, e.g. ^{137}Cs and ^{60}Co, have associated beta emissions. Beta detectors have a much lower background per unit area. As an example, for ^{137}Cs contamination, a 50 mm diameter, 50 mm thick sodium iodide scintillation detector will have a similar response, in terms of counts per second per Bq cm^{-2}, to a 50 mm diameter thin end window pancake GM detector. The background count rate from the sodium iodide detector will typically be 50 to 100 per second whereas the count rate from the GM detector will be around 1 per second. The signal from a beta detector is also much more dominated by the activity directly below the detector window. Background correction is also easy for a beta detector. Interposing a 4 mm aluminium plate between surface and detector will stop virtually all beta particles while leaving the gammas almost unaffected. This can allow a skilled user to assess beta surface activity even on a material with significant natural gamma activity. The same process does not work for gamma measurements.

6.41   The following measurement techniques are described, along with the relevant equipment.

♦ Bulk alpha monitoring
♦ Bulk beta monitoring

- Bulk gamma monitoring
- Direct alpha surface monitoring
- Direct hand-held surface beta monitoring
- Direct surface X and low energy gamma monitoring
- Tritium surface activity monitoring
- Surface monitoring by wipe (excluding tritium)

7.4 Activity Assessment using Sampling followed by Radiochemistry

6.42 In many circumstances, assessment of activity may not be possible without sampling followed by radiochemical treatment and analysis. This section addresses the procedures to be followed.

6.43 Note that analytical laboratories will normally quote results in Bq kg^{-1} whereas regulatory limits are generally in Bq g^{-1}.

7.4.1 Sample Collection and Preparation

6.44 The validity of the analytical programme will, in most cases, be reliant on appropriate sample collection and storage procedures.

6.45 Samples must be collected, preserved and stored in such a way as to prevent any significant change in the concentration and form of the radionuclides present. Such changes can include:

1. Loss of volatile radionuclides e.g. evaporation of tritiated water or loss of radon gas;
2. Loss of radionuclides such as ^{3}H and ^{14}C via biological degradation of organic compounds;
3. Changes in the physical and chemical form of the radionuclide;
4. Adsorption of the radionuclide onto the walls of the container;
5. Cross-contamination.

6.46 The procedures used for collecting the sample must be chosen such that the integrity of the sample and the activity concentrations of the radionuclides being analysed are not affected. This is particularly important when collecting samples for tritium analysis. If drilling is used to collect core samples, care must be taken during the sub-sampling stages to avoid material from the cut surfaces where loss of tritium (and other volatile radionuclides) may have occurred.

6.47 For certain analyses, the choice of storage bottle is important. Water samples collected for radon analysis must be collected in air-tight containers, using a set procedure to prevent loss of the radon gas. Samples collected for tritium analysis must be stored in air-tight containers or bags. Where practicable, solid samples containing tritium should be wrapped in aluminium foil before being transferred to the storage container.

6.48 If samples are to be stored for a period prior to dispatch to the analytical laboratory, some form of preservation may be required. Freezing the sample will help to prevent the loss of radionuclides via evaporation or bacterial degradation, whilst acidification of the sample may help prevent adsorption of actinides, for example, onto the container walls. However, acidification may result in the loss of radionuclides such as ^{129}I, ^{131}I etc. In some instances, particularly for aqueous samples, the analytical laboratory may recommend that a carrier is added to the sample prior to storage. For example, when measuring ^{90}Sr, it is advisable to add a

small quantity of stable strontium as a carrier. Again, such approaches should be discussed with the analytical laboratory.

6.49   It should be noted that a preservation procedure may affect any subsequent chemical separation procedures and it is therefore vital that any sample storage or preservation regimes are agreed with the laboratory prior to sample collection. In all cases, a record of any preservation undertaken must be accurately recorded and details supplied to the laboratory.

Table 6.1   Recommended sample preservation procedures

Analyte	Storage bottle type	Preservation	Storage times		Other information
			+4^{0}C	-20^{0}C	
Solids (non-biodegradable)					
Tritium & iodine	Polythene	Wrap in aluminium foil & double bag	30 days	6 months	Store in dark
Other nuclides	Polythene	None	4 months	> 1 year	Store in dark
Solids (biodegradable)					
Tritium	Polythene	Wrap in aluminium foil & double bag	NR	6 months	Store in dark
Other nuclides	Polythene	None	7 days	1 year	Store in dark
Aqueous samples					
Gross alpha/beta	Polythene	None	1 month	NR	
Gamma spec.	Polythene	None	2 days	NR	
Tritium	Polythene	none	2 months	NR	
Radon	Glass vial fitted with Viton seal	10ml mineral cocktail	1 day	NR	Return to laboratory as quickly as possible
^{14}C, ^{106}Ru	Glass	4g/1000ml NaOH			
Iodine isotopes	Glass	2ml sodium hypochlorite (10% w/v) / 1000ml	2 days	NR	
		Sodium thiosulphate	2 days	NR	
^{134}Cs & ^{137}Cs	Polythene	pH < 2 with HCl	6 months	NR	
Plutonium	Polythene	12.5ml c. HNO$_3$ /1000ml	6 months	NR	1 month maximum storage recommended in BS6068-6.3:2003
Actinides (e.g. Th, U, Np, Pu & Am)	Polythene (acid washed)	pH < 2 with HNO$_3$	6 months	NR	1 month maximum storage recommended in BS6068-6.3:2003

NR – not recommended

7.4.2 Sample Sizes

6.50   The quantity of sample required for analysis will depend on

♦   the analyses required

♦   the limits of detection (maximum missable activity) required

♦   the heterogeneity of the item being sampled

♦   specific requirements for sample archiving

6.51   The quantity of sample required for multiple radionuclide determinations can often be reduced by performing simultaneous separations on one sub-sample. However, this will depend on the analyses required and the procedures available to the laboratory. A summary guide to the quantity of sample required for various analyses is given below (although this will vary between laboratories).

Summary of sample masses and corresponding limits of detection

6.52   Table 6.2 and Table 6.3 give the minimum mass required to achieve the specified limits of detection for each nuclide group. In many instances, lower limits of detection are achievable if desirable although larger sample sizes may be required.

6.53   Smaller sample masses may also be analysed although the limit of detection will increase proportionally.

Table 6.2   Minimum Masses for Solid Samples

Group	Nuclides	Mass to achieve LOD (g)	LOD Bq g^{-1}
1	Gamma emitting nuclides	30g	0.001 typically
2	Gross alpha, Gross beta	5g	0.1
3	^{3}H and ^{14}C	10g	0.01
4	^{129}I	50g (can include the 30g from gamma spec)	0.05
5	^{55}Fe, ^{63}Ni, ^{99}Tc	5g	0.005 to 0.01
6	^{90}Sr	5g	0.01
7	^{210}Po	10g	0.0002
8	^{241}Pu, ^{239}Pu, ^{240}Pu, ^{238}Pu, ^{232}Th, ^{230}Th, ^{241}Am	5g	0.0002 (^{241}Pu - 0.01)
9	^{238}U, ^{236}U, ^{235}U, ^{234}U, ^{242}Pu	5g	0.0002
10	^{237}Np	5g	0.001
11	^{226}Ra	5g	0.001

Table 6.3   Minimum Masses for Aqueous Samples

Group	Nuclides	Mass to achieve LOD (g)	LOD Bq/kg
1	Gamma emitting nuclides	500g	0.05 typically
2	Gross alpha, Gross beta	500g	0.1
3	^{3}H and ^{14}C	50g	5 to 10
4	^{129}I	50g	50
5	^{55}Fe, ^{63}Ni, ^{99}Tc	100g	1
6	^{90}Sr	5g	1
7	^{210}Po	200g	0.005
8	^{241}Pu, ^{239}Pu, ^{240}Pu, ^{238}Pu, ^{232}Th, ^{230}Th, ^{241}Am	200g	0.005 (^{241}Pu - 0.05)
9	^{238}U, ^{236}U, ^{235}U, ^{234}U, ^{242}Pu	200g	0.005
10	^{237}Np	200g	0.005
11	^{226}Ra	100g	0.001

Note: The quoted 'minimum mass required' is the mass of sample required for the analysis of any/all the nuclides listed in that group. The figures above are provided as guidance only and the analytical service providers should be contact to confirm minimum masses prior to sampling.

6.54   To determine the total mass of sample required, identify the groups containing the nuclides required for analysis and sum the masses for each group. For example, if gamma spectrometry and tritium analysis is requested in a solid sample, the total sample mass required will be the minimum mass for groups 1 and 3 (i.e. 500g + 50g = 550g). If ^{14}C is also required additional sample is needed.

7.4.3   Sample matrices

6.55   Radioanalytical laboratories will have validated methodologies for the analysis of a wide range of common sample types. However, more unusual materials which often arise during decommissioning operations may be more difficult to analyse and pose particular technical problems. For non-standard sample types, always check that the analytical laboratory possesses validated procedures that are suitable for the matrix, or discuss any additional validation or testing studies that may be required prior to analysis of the sample.

6.56   Certain sample matrices pose a hazard to analytical personnel and specific precautions must be taken to overcome these hazards. Any samples containing a chemical (e.g. mercury, beryllium or asbestos), biological (sewage sludge) or radiological hazard must not be dispatched to the analytical laboratory without first notifying the laboratory and gaining permission to consign such materials. Appropriate warnings must be displayed on the sample containers and details of the hazard included in the accompanying paperwork.

7.4.4   Sample Transfer and Chain of Custody

6.57   The analytical laboratory must be notified prior to dispatch of samples. In particular, arrangements for receipt of radioactive materials (where appropriate) must be confirmed and all necessary paperwork completed. Details of the numbers of samples, physical form, estimated activity levels, potential hazards and analytical requirements should be forwarded to the laboratory ahead of the samples. Samples should be accompanied by a chain of custody form confirming the following details.

1.   The sample identification numbers (unique codes for each sample). Bar coding is effective.

2.   The date of sampling / reference date.

3.   Details of any specific hazards (these should be discussed with the analytical laboratory prior to dispatch of the samples).

4.   The analytical requirements.

5.   Details of any preservation or initial preparation procedures that have been performed on the sample.

6.58   The analytical laboratory should confirm receipt of the samples and provide details of any discrepancies between the reported and actual content of the consignment.

7.4.5   Sample Preparation

6.59   In most instances, some form of sample preparation is required before any analytical procedure is attempted. In some cases, the preparation procedures adopted could impact on the final results and the approaches used should be discussed with the laboratory.

6.60   Water samples often contain suspended particulate matter, which may hold many of the radionuclides of interest. It must be decided whether to filter the sample and analyse each component separately or to homogenise the sample and analyse the

total. This should be decided at the outset as quite different results can be obtained depending on the approach chosen.

6.61 For soil samples, the sample is often coarsely sieved to remove flints and any large debris. The mass of any material removed should be recorded and reported. However, if required, it is possible to grind and homogenise the total sample as received.

7.4.6 Homogenisation and sub-sampling

6.62 Once a fraction has been obtained for analysis, it must be homogenised. This may be performed either before or after further sample pre- treatment such as drying or ashing and this choice will depend on the analyses required. It is vital that the sample is homogenised prior to sub sampling to ensure that the measured aliquot is representative of the bulk sample.

6.63 In some instances (e.g. for mixed soft wastes) thorough homogenisation of the sample is impractical or impossible. In these cases it is advisable to take the entire sample for analysis. Where chemically similar alpha and beta emitting radionuclides are being analysed, it is often possible to leach the entire sample and produce a stock leachate which can be further sub sampled for individual alpha and beta radionuclide determinations. However, if chemically different alpha and beta emitting radionuclides are to be measured where different pre-treatment and or dissolution techniques are required for each analysis, it will not be possible to employ a universally acceptable leaching procedure. In this case, the entire sample is taken for gamma spectrometry to determine the total inventory of gamma emitting radionuclides. Sub samples are then taken for each analysis and each one is measured by gamma spectrometry to determine the proportion of the total gamma inventory present in the sub sample. All subsequent analytical results relating to the individual sub sample are then corrected back to the total sample using the gamma radionuclide data. This assumes that the fingerprint is essentially stable and that only the overall contamination level is varying and will introduce uncertainties where the activity could have undergone radiochemical separation to any degree.

7.4.7 Sample Drying and Ashing

6.64 Samples are often dried to a constant weight before analysis to overcome effects from variable water content. Drying also produces a sample that is more stable during storage. Both freeze-drying and oven drying may be used, although freeze-drying avoids thermal decomposition of the sample. However, sample drying will lead to the loss of tritiated water along with certain other volatile radionuclides; the magnitude of the loss will depend on the approach used.

6.65 In addition many techniques require that organic matter is removed by ignition. Again volatile radionuclides may be lost during ignition depending on the ignition temperatures used. Typical radionuclides that may be lost during ignition are ^{3}H, ^{14}C, ^{35}S, ^{99}Tc, ^{103}Ru, ^{106}Ru, ^{137}Cs and ^{210}Po.

7.4.8 Sample Dissolution

6.66 Most radioanalytical techniques for the measurement of alpha or beta emitting radionuclides begin with a sample dissolution stage. Often this simply involves leaching the sample with a suitable acid such as nitric acid, hydrochloric acid or *aqua regia*. However, some forms of plutonium and mineral-bound uranium and thorium will not be effectively solubilised in this way and a more aggressive dissolution procedure is required. Total sample solubilisation, often employing hydrofluoric and/or perchloric acids, is widely used. Alternatively, the sample may

be mixed with a flux such as lithium borate or potassium hydrogen fluoride and the mixture fused at high temperatures to produce a melt. The specific approach chosen will depend on the sample type and the radionuclides analysed and in some instances can significantly affect the final result.

7.4.9 Gamma Spectrometry

6.67 Gamma spectrometry is used to measure a wide range of gamma emitting radionuclides including:

Activation products: ^{51}Cr, ^{54}Mn, ^{55}Fe (via X-ray using low energy gamma spectrometry), ^{59}Fe, ^{60}Co, ^{65}Zn, ^{134}Cs

Fission products: ^{131}I, ^{137}Cs

Actinides: ^{241}Am, natural uranium and thorium decay chains

6.68 Gamma spectrometry requires minimal sample preparation and no separation chemistry. The sample (usually dried or freeze-dried, although fresh samples can be analysed) is packed into a container and placed onto the gamma spectrometry system. Typically high purity germanium detectors (hpGe) are used, which require cooling with liquid nitrogen. Sodium iodide (NaI) crystals are also used as they do not require cooling with liquid nitrogen and have higher detection efficiencies compared with hpGe detectors. However, the energy resolution of these systems is not as good, making all but the simplest spectrometry impossible and leading to poorer background rejection. Typically, gamma spectrometry systems can detect photons down to *ca.* 40 keV although lower photon energies associated with e.g. ^{55}Fe or ^{129}I can be measured if a special window is fitted.

6.69 Data acquisition and spectrum analysis is often performed automatically with manual checking of the data. The response of the detector and hence the efficiency calibration will depend on the following:

♦ the energy of the gamma photon

♦ the size of the crystal

♦ geometry of the sample

♦ sample density (particularly a problem for low energy gamma emitters such as ^{210}Pb and ^{241}Am)

6.70 Counting efficiencies over the energy range for a given geometry and sample density are usually determined by preparing matrix-matched standards containing a range of radionuclides. ^{241}Am is often included to provide a low energy calibration point and a standard solution containing a wider range of radionuclides has become available. Some laboratories still use a ^{152}Eu calibration source, which has a number of gamma emissions covering wide energy range. However, this standard is particularly prone to coincidence summing (see next section).

6.71 In addition, spuriously low activities can be obtained for gamma emitters with more than one gamma emission. In certain instances the two emissions are not distinguished by the detector and are recorded as one event with energy equal to the sum of the two individual energies deposited. Where both events are photoelectric, a clear sum peak is produced. However, for high energies, most will be the consequence of at least one Compton event and will generate a pulse at an energy below that of the sum of the two emission energies. This is known as *coincidence* or *cascade summing* and is a particular problem for ^{134}Cs and some rare earth radionuclides.

6.72 Gamma spectrometry is often used for the measurement of natural radionuclides of the uranium and thorium decay chain. Usually, gamma emissions from daughter radionuclides are used to infer activities of the uranium and thorium parents.

However, it is important to remember that any loss of radon from the sample may result in a decay chain that is not in secular equilibrium and measurement of e.g. ^{214}Pb at the end of the chain may not give an accurate representation of uranium content of the sample. In addition, purified uranium cannot be measured reliably using the gamma spectrometric measurement of daughter radionuclides as their activities will be dramatically below that of the parent uranium. It should also be noted that ^{226}Ra has a similar gamma emission energy to ^{235}U and, unless significant quantities of ^{235}U are present, it can be difficult to deconvolute the two radionuclides.

7.4.10 Alpha Emitters

6.73   The following radionuclides are routinely measured using alpha counting:

^{224}Ra, ^{226}Ra, ^{230}Th, ^{232}Th, ^{234}U, (^{235}U, ^{236}U), ^{238}U, ^{237}Np, ^{239}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, ^{242}Cm, ^{244}Cm, ^{252}Cf

6.74   Although alpha spectrometry is possible, the energy of an alpha particle will be significantly attenuated through any interaction with surrounding matter, resulting in severely degraded spectra. It is therefore necessary to separate the alpha emitter of interest from the bulk of the sample and produce a thin source suitable for alpha counting. Counting in vacuum also improves the performance.

6.75   In some cases, there are spectral overlaps between alpha emitters of different elements, which can only be overcome through chemical separation of these elements. However, for energy overlaps between different radioisotopes of the same element deconvolution is not routinely possible (e.g. ^{239}Pu and ^{240}Pu or ^{235}U and ^{236}U cannot be readily resolved by alpha spectrometry). **Yield monitors** are added prior to any chemical separation to determine the loss of the analyte during the separation. Usually the yield monitor is an isotope of the element being analysed that would not be expected at significant activities in the sample. In the case of curium isotopes, the chemistry of curium and americium are sufficiently similar that ^{243}Am can be used as the yield monitor. Where possible, an alpha emitter is chosen to permit simultaneous measurement of the yield monitor with the unknown radionuclide.

6.76   This is not the case for ^{237}Np where the beta emitting ^{239}Np is often used as a yield monitor and separate measurements of the two radionuclides are required.

6.77   Chemical separation usually employs a number of separation stages designed to isolate the radionuclide of interest from the bulk of the sample. Precipitation, solvent extraction, ion exchange and extraction chromatography are all routinely used to achieve such a separation. Final **source preparation** is achieved in one of two ways. The alpha emitter may be electrodeposited onto a disc or may be co-precipitated with a rare earth fluoride to produce a fine source suitable for alpha counting. Electrodeposition produces a robust source that may be readily archived. However, the approach is relatively time-consuming. Fluoride precipitation is much more rapid but the source is not as robust.

6.78   Measurement of the final source is usually achieved using **alpha spectrometry** and employing ion-implanted detectors in a vacuum. The system is capable of very low limits of detection and provides spectral information. Alternatively gross alpha measurements can be made using either **gas flow proportional counters** or **zinc sulphide screen scintillation** detectors. More recently alpha / beta discriminating **liquid scintillation** counting has been used for the measurement of alpha emitters and has been successfully applied to radium and radon analysis and to assessment of total alpha activity in aqueous samples.

Beta Emitters (and certain electron capture radionuclides)

Activation products: ^{3}H, ^{14}C, ^{35}S, ^{41}Ca, ^{45}Ca, ^{55}Fe, ^{63}Ni

Fission products: ^{89}Sr, ^{90}Sr, ^{99}Tc, ^{129}I, ^{147}Pm

Actinides: ^{241}Pu

6.79   The energy of the beta decay is split between the beta particle and the anti-neutrino, producing a wide band of possible beta particle energies from essentially zero up to the maximum decay energy. This is more difficult to analyse by spectrometry when compared to the discrete energies encountered for gamma and alpha decays. Analysis of beta emitters therefore relies on the chemical separation of the specific element followed by a beta measurement of the purified fraction. Limited spectral deconvolution is possible if the energy of the beta decay events is significantly different, allowing the quantification of e.g. ^{89}Sr and ^{90}Sr in the same source. As with alpha spectrometry, a yield monitor is often added to correct for any losses of the analyte during chemical separation, although in many case the yield monitor is normally the stable element analogue of the radionuclide being analysed. For some determinations, a gamma emitting radioisotope of the element can be used where the gamma emission has a negligible effect on the beta measurement (e.g. ^{85}Sr for ^{90}Sr determinations) or where the gamma emitting radioisotope has a sufficiently short half-life that it may be left to decay before the beta measurement is performed (e.g. ^{99m}Tc for ^{99}Tc measurements). Again chemical separation is often a combination of precipitation, solvent extraction, ion exchange chromatography and / or extraction chromatography.

6.80   Final measurement of beta activity is often performed using a gross beta counting technique such as ***gas flow proportional*** counting, ***anthracene-screen scintillation*** counting or ***Geiger-Müller*** tube. Alternatively ***liquid scintillation counting*** is widely used giving high counting efficiencies and sensitivity to low energy beta emitters.

6.81   Measurements of low-energy beta emitters, such as ^{3}H, ^{14}C, ^{63}Ni etc and for very low energy X-ray emitters such as ^{55}Fe are best performed using liquid scintillation counting although interference from chemiluminescence may give erroneous results if not carefully corrected for. For high-energy beta emitters such as ^{90}Sr (or more accurately the ^{90}Y daughter), Cerenkov counting can be used, resulting in lower backgrounds and overall reduced Maximum Missable Activity.

7.4.11 Analysis of Tritium

6.82   Analysis of tritium in samples is particularly complex. The choice of analytical technique will depend on the chemical form of the tritium and the sample matrix. For aqueous samples, distillation is often used to purify a fraction of water prior to tritium analysis. The water may be made alkaline prior to distillation to prevent volatile radionuclides from distilling over. However, tritium bound to organic molecules may not distil over and may be missed. For solid samples, a number of approaches have been used. The sample can be soaked in water and the amount of tritium leached into the water measured. This works reasonably well for samples that are surface contaminated with tritiated water. However, if the contamination is not as tritiated water or the contamination is associated with the matrix of the sample a total sample decomposition procedure is preferable. This usually involves decomposing the sample either chemically or thermally in a combustion furnace, and converting all liberated tritium species to tritiated water that is subsequently trapped and measured.

The choice of method will largely depend on the most likely form of the contamination and the analytical budget.

7.4.12 Gross Alpha and Beta Measurements

6.83   Gross alpha and beta measurements are crude assessments of the alpha and beta activity of the sample.

6.84   The measurement is usually performed on a sample following minimal sample pre-treatment. Normally gas flow proportional counting is used to determine the alpha/beta activity although alpha/beta discriminating liquid scintillation counting is also used particularly for screening water samples. The instrument is calibrated against one alpha emitting (U, plutonium or ^{241}Am) and one beta emitting radionuclide (^{40}K or ^{137}Cs) and the response of the instrument will vary depending on the calibration radionuclide chosen.

6.85   The technique does not take into account any difference in instrument response with energy and is totally insensitive to low-energy beta emitters such as ^{3}H, ^{14}C, ^{63}Ni etc. Sample composition and particle size may also affect the instrument response.

6.86   The technique should only be treated as a screening procedure and should be followed by individual radionuclide analysis if elevated activities are detected.

6.87   Widely varying gross alpha and beta results have been observed for soils which are attributable to variations in the natural radionuclide content of the soils. In many cases, this wide variability is linked to the variation in clay content where a significant proportion of natural uranium and thorium can reside. To subtract this effect from any enhancement in alpha and beta activity associated with operational deposition, it is possible to derive a correlation between the natural gross alpha and beta activity and certain elements that are indicative of clay content (e.g. rubidium). Such a correlation must be assessed for each site. X-ray fluorescence analysis is particularly effective for this purpose.

7.4.13 Non-Radiometric Techniques

6.88   Non-radiometric techniques have been widely used for the quantification of radionuclides. The techniques are usually most effective for the measurement of long-lived radionuclides such as ^{99}Tc, ^{129}I, U, Thorium, ^{237}Np and plutonium. In addition, mass spectrometric techniques often permit the more precise determination of isotope ratios (e.g. ^{238}U:^{235}U or ^{232}Th:^{230}Th ratios) and, unlike alpha spectrometry, can distinguish between ^{239}Pu and ^{240}Pu. Non-radiometric techniques include fluorimetry, inductively coupled plasma mass spectrometry (ICP-MS, high resolution ICPMS and multi collector ICPMS), thermal ionisation mass spectrometry (TIMS), secondary ion mass spectrometry (SIMS), resonance ionisation mass spectrometry (RIMS) and accelerator mass spectrometry (AMS).

6.89 Mass spectrometry operates by detecting atoms, not emissions. As a simple rule, the minimum detectable activity (Bq) is approximately equal to 0.3 divided by the half-life in years. MC-ICPMS is more sensitive than alpha spectrometry for nuclides with half-lives greater than approximately 300 years. This is shown in Figure 6.3 (below).

Figure 6.3   MC-ICPMS minimum detectable activity versus half life
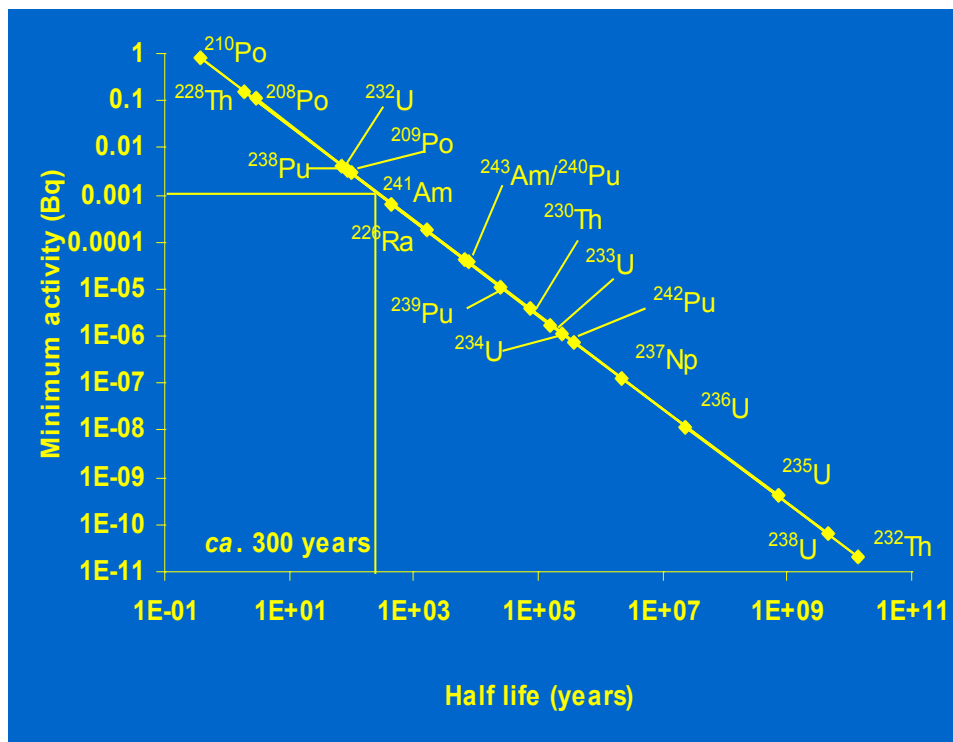
6.90 In many cases, results from non-radiometric analyses are reported in terms of concentration rather than activity. The following equation can be used to convert from mass concentration to activity concentration.

Activity (Bq/kg) = (Mass fraction (ppm) x 4.17 x 10^{20})/(A x t)

6.91 Where A is the atomic weight of the radionuclide and t is the half-life of the radionuclide in seconds.

7.4.14 The Performance of a Method

Sensitivity:

6.92 A measure of the resolving power of a method. Sensitivity is dependent on the instrument efficiency, typical chemical recovery and the amount of sample taken for analysis.

Accuracy and Precision:

6.93 Accuracy is a measure of how close the measured value is to the 'true' result, whilst precision is a measure of the scatter of results for repeated analyses.

Figure 6.4   Illustration of precision and accuracy
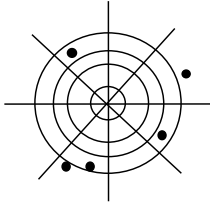
Poor accuracy
Poor precision
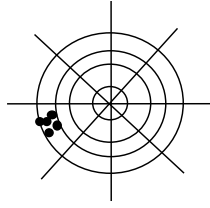
Poor accuracy
Good precision
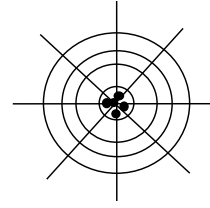
Good accuracy
Good precision

Uncertainties:

6.94   An analytical result is normally quoted along with an uncertainty at a given confidence level (quoted as either a percentage or a number of standard deviations). For example, a result of 10 ± 1 Bq/kg at the 95% confidence level indicates that we are confident at this quoted level that the true result is somewhere between 9 and 11 Bq/kg. Uncertainties are often only quoted based on counting statistics and refer only to the measurement. However, uncertainties arise at all stages of the analytical procedure and a more meaningful calculation of uncertainty includes all these method uncertainties. Typically, method uncertainties are around 5 – 10% of the measured value.

Limits of detection:

6.95   The **limit of detection** is defined for a given measurement process as the smallest true net count rate that is 'certain' to be detected with a specified degree of confidence (i.e. effectively, in many cases, the maximum missable activity).

6.96   The **minimum detectable concentration** (MDC) is the detection limit corrected to units of Bq per unit volume or mass of sample.

6.97   A number of factors affect the limit of detection:

♦   Method used for calculation

♦   Instrument background

♦   Counting efficiency

♦   Amount of sample analysed

♦   Length of count time

6.98   In general, lower limits of detection result in higher analytical costs.

7.4.15 Quality Control

6.99   It is normal to monitor the performance of an analytical procedure through the analysis of some or all of the following:

♦   method blanks

♦   spiked sample controls

♦   in-house reference materials

♦   certified reference materials

6.100 It is important to agree how frequently these controls will be run at the beginning of the analytical programme.

7.4.16 Sample Archiving and Disposal

6.101   In many cases a sub-sample is taken for analysis and it is therefore important that the customer agrees with the laboratory how the remaining sample will be stored. When reviewing sample archiving requirements it is important to consider what additional analyses may be required and any implications to the storage procedure adopted.

7.5   Summary of Issues Relating to the Development of an Analytical Approach

6.102   There is a wide range of analytical techniques available for radionuclide analysis. To ensure that the data is 'fit for purpose' it is vital that the most appropriate technique is used. To ensure this, the analytical laboratory must be involved at the initial stages of project development.

Agree on the following aspects of the analytical programme:

♦   Any specific sampling and preservation procedures that may be required prior to dispatch to the analytical laboratory

♦   The appropriate containers to store the samples

♦   The method for sample transport to the analytical laboratory and implementation of chain of custody forms

♦   The most appropriate analytical technique for the nuclides being investigated

♦   Specific sampling and storage requirements and the amount of sample required

♦   Sub-sampling, preparation and dissolution procedures

♦   Specific procedures that may be necessary to overcome heterogeneity issues

♦   Potential interferences

♦   The required sensitivity, precision and detection limits

♦   Methods for calculating uncertainties and detection limits

♦   Quality control

♦   Timescales / deadlines

♦   The method used to report the results (e.g. interim results reported electronically followed by a signed report)

8   Sampling Strategy

8.1   Sampling for sentencing purposes

8.1.1   Sampling strategy

7.1   Sampling strategy in support of a sustainable approach to material use and waste management in the nuclear industry can be defined as follows:

   ♦   generation of a sampling plan that will provide demonstrable compliance with the regulatory requirements for clearance of materials; and,

   ♦   ensuring that the sampling and assessment process is robust and defensible.

   Where there is a high level of confidence that the waste or material is non-radioactive (e.g. based on knowledge of the provenance of the article or substance in question), then monitoring is undertaken for reassurance purposes only and there is no need to apply statistical methods to the outcome.

7.2   An example of this situation might be monitoring of people as they leave a controlled area.   The normal precautions to control contamination risk are considered sufficient to allow people to leave the area without going through a formal sentencing process.

   Where there is any reasonable doubt about the history of the material and the potential for it to have been contaminated or activated, then it should be assumed to be potentially radioactive and subject to the appropriate sentencing process from Chapter 5.

7.3   In order to make sentencing decisions on the basis of sampling, the data acquired must be considered to be reliable and represent the material being sampled.

7.4   In cases where each of the individual sampling results indicates activity levels well below or well above the action limit, taking into account the overall uncertainty associated with each result, it is fairly obvious what the sentencing decision should be: either the material being sampled is itself below or above the action limit.   In cases where the sampling data are close to the action limit, and their overall uncertainties cannot be ignored for the purpose of making the sentencing decision, it is less clear what the sentencing decision should be.   In these cases, a statistical approach is required to support the sentencing decision.

7.5   The statistical approach to sentencing requires that a numerical level of confidence in the sentencing decision is defined, and the sampling data are compared against this level of confidence in order to determine whether the material being sampled is above or below the action limit.   The user defines the probability that the sentencing decision is correct and the probability that the sentencing decision is wrong.   The sum of both probabilities must be 100%.

7.6   The approach summarised here applies where 100% monitoring is not practicable and a series of discrete samples needs to be collected.

7.7   Figure 7.1 summarises the steps that should be followed in order to construct a robust statistical approach, and it is the starting point for development of the detailed sampling strategy to be adopted.

Figure 7.1   Sequence of activities for any statistical sampling procedure

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                    ┌─────────────────────────────────────────┐
                    │   Step 1: Pre-characterisation          │
                    └─────────────────────────────────────────┘
                                      │
                                      ▼
                    ┌─────────────────────────────────────────┐
                    │   Step 2: Determine sampling objectives │
                    └─────────────────────────────────────────┘
                                      │
                                      ▼
                    ┌─────────────────────────────────────────┐
                    │   Step 3: Define the acceptable         │
                    │   significance levels for about the     │
                    │   sentencing of material                │
                    └─────────────────────────────────────────┘
                                      │
                                      ▼
                    ┌─────────────────────────────────────────┐
          ┌────────▶│   Step 4: Define the sampling zone/areas│
          │         └─────────────────────────────────────────┘
          │                           │
          │                           ▼
          │         ┌─────────────────────────────────────────┐
          │         │   Step 5: Characterise expected         │
          │         │   distribution of contamination in each │
          │         │   zone/area based on existing knowledge │
          │         └─────────────────────────────────────────┘
          │                           │
          │                           ▼
          │         ┌─────────────────────────────────────────┐
          │         │   Step 6: Define sampling strategy based│
          │         │   on expected distribution of           │
          │         │   contamination                         │
          │         └─────────────────────────────────────────┘
          │                           │
          │                           ▼
          │         ┌─────────────────────────────────────────┐
          │         │   Step 7: Sample, analyse and assess    │
          │         │   data                                  │
          │         └─────────────────────────────────────────┘
          │                           │
          │                           ▼
          │                      ◇ Compare ◇
          └──────────────────── ◇ results with ◇
   Assumptions clearly            ◇ expected ◇
   not correct                    ◇ distribution of ◇
                                  ◇ contamination ◇
                                       │
                          Assumptions broadly correct
                          ┌────────────┴────────────┐
                          ▼                         ▼
          ┌───────────────────────┐   ┌───────────────────────────┐
          │  Step 8a: Sentence    │◀─▶│  Step 8b: Document process│
          │                       │   │  leading to sentencing    │
          │                       │   │  decision                 │
          └───────────────────────┘   └───────────────────────────┘
```

8.1.2 Uncertainty and Variability

7.8   Uncertainties will arise in field measurements, material sampling and laboratory analyses. Localised heterogeneity in the distribution of contamination will also be reflected in the sample results. These should all be considered when making judgements about overall confidence in results obtained and sentencing decisions.

7.9   In general, the uncertainties in the laboratory analysis are normally much smaller than those which may arise from, for example, field monitoring and sampling.

7.10   Uncertainties introduced by the way in which material samples are taken can be minimised by following a set protocol, as outlined here. This will also minimise the effects of local heterogeneities in the distribution of contamination.

The sampling process itself must be carefully designed because this is the source of the greatest uncertainties.

7.11   This Section details the steps necessary to obtain a statistically robust and defensible analysis of the overall activity concentration in material, which can then be

compared with the relevant limit or constraint. There is no need for a detailed knowledge of statistics to be able to apply the methods given. However, detailed summaries of the statistical methods used are included in Appendix D for those who wish to read them.

8.2   Sampling to establish fingerprints

8.2.1 Principles

7.12   There are some important differences between sampling in order to establish a fingerprint and sampling to determine absolute activity levels in a waste or material for sentencing purposes.

7.13   In producing a fingerprint we are most interested in the ratios of the activities of the various radioactive species, and the overall level of activity in each sample is of lesser importance. If on the other hand sampling is being carried out to determine the level of activity in the waste or material it is unlikely that full analysis for every likely radionuclide will be requested since the fingerprint, if appropriate, should already be documented and the activities of only a relatively small number of radionuclides are of interest. In this latter example, the activity of one key radionuclide will be referenced against the fingerprint to determine the overall activity in the waste or material*, and measured activities of any other radionuclides will be used as a check on the continued adequacy of the fingerprint only. Nonetheless, the validity of the applied fingerprint must always be verified.

7.14   Sampling work for fingerprinting should adhere to the same general principles set out in Section 8.1 with the following exceptions:

  ♦ the location of the samples should necessarily be biased towards known areas of contamination which have been zoned from reference to historical information and non-destructive measurements;

  ♦ the sampling regime should aim to gather sufficient activity in order to define the relationship between the radionuclides; and,

  ♦ statistical analysis, as presented in Chapter 10 (and Appendix D) should <u>not</u> be used to determine the number of samples taken.

7.15   Ideally, any fingerprinting work should ideally be carried out prior to decontamination work which might alter the spread and relative activities of the various radionuclides. However, it is important to realise that the decontamination process can change the fingerprint, particularly if the chemistry of the radionuclides is very different.

8.2.2 Zoning

7.16   For any fingerprint it is essential to consider its scope, and to ensure that it is not being applied unreasonably. The scope of the fingerprint should typically be defined with reference to a specific geographical area or process, however if the conditions in the waste or material were to change such that the activity of one or more radionuclides were to fall relative to the others, it would be inappropriate to continue to apply the fingerprint without further consideration.

7.17   For fingerprinting purposes, taking samples with little or no measurable activity will not provide meaningful information about the relative activities of radionuclides of

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*   See Chapter 10. On occasion more than one radionuclide may be regarded as key indicators within a fingerprint.

interest. It is recommended that samples be taken from areas of the waste or material where there is known contamination, preferably at levels which will be measured above the receiving laboratory's limits of detection without exceeding safe limits for transport, preparation and analysis. The location of these areas may be informed by historical information on routine and fault scenarios involving contact with radioactive material, but should be confirmed from measurements of the waste or material by non-destructive means, for example hand-held Health Physics instruments, gamma imaging devices etc. The choice of instruments should, in turn, also be informed by the operational history of the waste or material. Certain radionuclides may comprise a significant percentage of the overall activity but require particular instruments to confirm their distribution over the waste or material. It should be remembered that as with radiochemistry, you only see what you look for. For example, searching with a beta probe will find beta emitting nuclides but will not find electron capture nuclides. Hence it is important to take samples not just on the basis of one search instrument if the fingerprint is at all complicated.

7.18   As in the case of sampling to determine absolute activity levels, for fingerprinting purposes each zone of the waste or material should be defined precisely and unambiguously. For fingerprint development, the term zone may refer to a physical area where the waste or material arises, or even a particular fraction of the waste or material itself. In order to establish a fingerprint it is essential to determine that the radionuclide activities within a particular zone are reasonably correlated. Good quality information on the likely distribution of activity (essentially the operational history of the material supported by local monitoring work) adds credibility to any decisions on what constitutes a reasonable correlation. For certain wastes or materials or sub-divisions of such wastes or materials there might be no relationship between the activity of the different radioactive species, in which case it may be necessary to measure the relevant species independently, and abandon the concept of a fingerprint altogether.

7.19   This is not to say that the relative activities of radionuclides within a contaminating mixture are expected to be constant for all wastes or materials. Throughout the volume of the article or substance being assessed, it is anticipated that there will always be some degree of variation or uncertainty between the activities of radionuclides predicted by application of the fingerprint, and the true activities for single items. For fluids such as well-mixed liquids or semi-solid sludges the degree of uncertainty in the fingerprint will be fairly low since contamination should be homogenously distributed at the point of sampling. Similarly, fingerprint uncertainty for an item such as a vessel which has only ever been exposed to uniform distributions of homogenously radioactive materials (especially liquids) will be low. For all other solid materials it should be expected that contamination will be randomly deposited over a number of years, and subsequent processes such as radioactive decay will change the relative ratios of radionuclides present. Therefore fingerprints developed for solid wastes or materials tend to represent a 'best estimate' of the contaminating mixture and it should not necessarily be surprising that fingerprint uncertainty is higher for solid materials than it is for homogeneously contaminated liquids. The use of fingerprints is a pragmatic industry-standard approach to waste or material characterisation which avoids the need to carry out full radiochemical analysis on every item generated, which, in any case, may not be practicable. What is important is to determine which nuclides dominate the sentencing decisions and which are peripheral. Any fingerprint confirmation measurements should concentrate on the important ones.

7.20   Where the distribution of contamination within the waste or material is truly random, and there is no indication of either a particular type of contamination or elevated levels of contamination within a known location, the potential for contamination throughout the volume of the article or substance is considered to be even. In

these cases, it is valid to establish a fingerprint from reference to the average analysis result for a group of samples taken throughout the volume of the waste or material, provided all samples are taken and treated similarly and given equal weighting. It is acceptable to combine the samples prior to analysis, since this leads to an average fingerprint, however it is recommended that individual samples should be analysed in order to determine whether it is appropriate to establish further zones with their own unique fingerprints.

7.21   Where the absolute level of activity associated with each sample is very low, some nuclides may be detectable and others may be below the maximum missable activity. In such cases, sufficient information may be obtained from the positive determination, but it may also be appropriate to present a bulked collection of samples to the laboratory for analysis.

7.22   While the provenance of the material of interest may suggest that there is only one zone for fingerprinting purposes, it is recommended that any analytical results acquired should be reviewed critically in order to confirm this position. This recommendation is particularly relevant to large volume materials. The sample results should be interpreted carefully in order to establish whether further zones may be appropriate. It is useful to look carefully at the ratios between the most important radionuclides for each of the sample results, and establish whether similar sample results may be associated with particular materials or items that are geographically close or have similar provenance. It is especially useful to present the key ratios of prominent radionuclides graphically (e.g. a Box Plot) since this gives a much clearer indication of similarities or differences between the sample results. Where there are outliers (that is, isolated sample results that are clearly different to other results) these should be investigated further and possibly more samples should be taken to confirm whether they represent a trend in the results or are genuine one-off occurrences.

7.23   When the sample results indicate that it may be appropriate to develop further fingerprints, the sampling strategy should be re-considered, and re-planned as necessary. In other words, having started with a number of assumptions about how many fingerprints may be applicable, samples are taken and the analytical data are reviewed. If the data don't necessarily support the initial assumptions then the assumptions are revised and supported by further sampling until such point as the sampling data agree with the assumptions.

7.24   Determining how many samples to take when establishing a fingerprint depends largely on the number of potential zones, the volume of waste to be disposed (or material to be sentenced for reuse), and similarities between the different analysis results from previous phases of sampling and analysis. As with the sampling approach used to define the activity in defined zones, fingerprinting may require that sampling follows an iterative pattern until the analysis results for appropriate zones are tolerably consistent. Further zones may be established and more samples taken in support of each zone if it is found that there are significant differences in the analysis results. The size of each sentencing volume and the degree of homogeneity within the sentencing volumes should also be considered.

7.25   Other factors such as the budget and timescale for completing the work, as well as the safety implications of taking and managing the samples will necessarily have an impact on the number of samples taken. It is important however, that technical considerations continue to be properly considered. Fingerprints must be prepared to the satisfaction of the person with overall responsibility for characterising and sentencing the materials.

7.26   The samples need not be taken from the waste or material which they are intended to characterise if the contaminating mixture of radionuclides can be measured

directly at source, or in some other form unaffected by the effects of further contamination or loss of particular radionuclides. This is particularly the case where levels of contamination over the volume of the waste or material are so low that they cannot readily be detected using portable measurement instruments. For example, in a radiologically designated facility where the nature of contamination is readily disturbed and may be made airborne, it may be appropriate to sample the filters on the exit airflow if there is no detectable localised activity within the facility. For this strategy to be fully acceptable there should be no other sources of contamination entering the ventilation system or suspected radionuclides in the waste or material which would not be constrained within the ventilation filter medium. Furthermore, the length of time that contamination was deposited on the surrogate medium (in this case a filter) should be considered since this may not necessarily correspond with the nature of contamination on the materials to be sentenced.

8.2.3 Variability / Exclusions

7.27   For the purpose of applying the fingerprint, the limit of variability must be deemed to be acceptable. Furthermore, the scope of each fingerprint must be defined at a level that provides a balance between the effort required for its development and the benefits and risks associated with variation within the material. Of particular interest is the risk of incorrectly categorising waste for disposal purposes. Variability within the fingerprint is just one component that must be allowed for in the sentencing process.

7.28   Tritium is a special radionuclide. It tends to be more widely dispersed than other radionuclides since it may be present as a gas or as water vapour. Tritium tends to penetrate various materials rather than remaining fixed on the surface, and certain materials that contain hydrogen have greater affinity for tritium than materials such as metals. For any materials where tritium is suspected, it is important to consider whether it is appropriate to include tritium within the fingerprint at all since it may not necessarily be well correlated with the remaining radionuclides. Further analysis would be required to determine tritium activity within the material of interest, and application of the fingerprint alone would be insufficient. Any radionuclides which are deliberately omitted from the scope of a fingerprint and require further analysis should be clearly notified in the official record of the fingerprint (e.g. it is acceptable to prepare the fingerprint for the purpose of estimating total activity with the exception of tritium).

8.2.4 Precision Levels

7.29   There is no definitive position on the level of precision that should be applied when recording individual radionuclides' contribution to total activity in a fingerprint. Again, the objectives of the fingerprinting study should be referred to, and any specific requirements of external receiving organisations or regulators should be acknowledged.

7.30   The number of significant figures used to record the absolute or specific activity of each radionuclide (say, in an analysis report or historical record) should not be exceeded when recording the percentage activity attributed to that radionuclide in the fingerprint. For example, if a sample from a material to be fingerprinted was analysed, and the ^{137}Cs activity was recorded at 0.134 Bq g^{-1} (i.e. to three significant figures), it would be inappropriate to record the contribution from ^{137}Cs to total activity at, say, 45.003% (i.e. to 5 significant figures). Where rounding is undertaken, the total should still add up to 100%.

7.31   As a general rule, understanding that fingerprints tend to be 'best averages' of the relative ratios of radionuclide activities in the material to be assessed, and there is

variation in the true ratios of radionuclides throughout the material, it is inappropriate to record the percentage activity of each radionuclide in the fingerprint to more than three significant figures (i.e. if percentage activities are expressed as a number to the power of a base-ten logarithm, the number of figures before and after the decimal point should not exceed three).

9   Radiochemical analysis of samples

8.1   The range of analysis should include all radionuclides suggested by the history of the waste or material, plus additional radionuclides which it is reasonable to expect as a result of unrecorded fault scenarios or cross-contamination events. Gamma spectrometry is a very useful tool in that it is generally straightforward to perform and records a range of different radionuclides. However, there are many cases where gamma rays with similar energies are emitted by different radionuclides which can cause confusion. This applies to naturally occurring radionuclides where the equilibrium has been disturbed, for example, and particularly to ^{226}Ra and ^{235}U. Hence some knowledge of the likely fingerprint may be essential for a realistic assessment of the gamma nuclides present. Similarly, gross alpha and gross beta analysis may be performed with relative ease and although they do not provide activities for individual radionuclides they do give a rough indication of the nature of contamination for comparison with other information sources. Further analysis for specified radionuclides such as tritium, ^{90}Sr or ^{55}Fe requires a degree of chemical preparation prior to analysis which will delay the reporting of results and increase the cost of analysis, but is the only way to determine them accurately. It is also worth noting that where plutonium is suspected in the fingerprint, alpha spectrometry will measure each of the plutonium isotopes with the exception of ^{241}Pu. Separate analysis will be required to determine ^{241}Pu.

8.2   Radionuclides which are reported by the analysing laboratory should always be interpreted carefully. While it is reasonable to question the presence of radionuclides which were not anticipated in the fingerprint, it is equally important to keep an open mind and be prepared to re-submit further samples to confirm the presence of unusual or unanticipated radionuclides.

8.3   Information on laboratory analysis uncertainties should always be obtained from the laboratories that carry out the work. Data on precision, accuracy and bias should be provided as part of their service in accordance with the relevant British Standard.

8.4   By following Relevant Good Practice, cross contamination, misidentification of sample results and errors on the part of the analysing laboratory should be minimised. Nonetheless, key issues worth checking in the laboratory report include:

♦   Are the identities of the samples correct in the report?

♦   Are the units for each radionuclide's activity correct?

♦   Have radionuclides with short half-lives been reported which could not possibly be present in the waste or material due to the time since likely formation?

♦   Have radionuclides been reported which could not possibly be present in the waste or material due to lack of a contamination mechanism?

8.5   Where a certain radionuclide has not been reported above limits of detection, it should not be implied that the limit of detection is a real value. The true activity of the given radionuclide may be anywhere between zero and the limit of detection reported by the analysing laboratory. Interpreting limits of detection as real values produces a skewed fingerprint where the relative ratios of radionuclides are a function of the ability of the laboratory to analyse small activities of material. In these circumstances it may be appropriate to disregard the particular radionuclide entirely or request further analysis using a longer count time or a more precise technique. It is important to ask the question "Would including or excluding this radionuclide from the fingerprint affect the final decision made on the basis of an activity assessment?"

8.6   In interpreting the results from analysis, the following points should be noted for the purpose of compiling fingerprints:

♦   For uranium and plutonium, unless the material is associated with single isotope production facilities, a range of isotope activities should be recorded.

♦   Where uranium is present, activities of ^{234}U, ^{235}U and ^{238}U should be declared as a minimum. Further isotopes may need to be recorded if the radioactive material is or has been contaminated with irradiated fuel. If it is possible to infer the enrichment of the uranium from reference to records, this must agree with the analytical results, taking account of the relative precision of both figures. If there is poor agreement, it is appropriate to question the analytical results and/or the sampling procedure however where records and analytical data do not agree, any assumptions leading to final decisions on the enrichment of uranium must be documented.

♦   Where plutonium is present, activities of ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu should be recorded as a minimum. Activities of further isotopes may be recorded if they have been reported by the analysing laboratory, although this would tend to be rare. It is difficult for laboratories to report ^{239}Pu and ^{240}Pu separately since the energies of their alpha emissions are so similar. Further data sources such as decay-corrected burn-up codes may be required to determine activities of all plutonium isotopes. Due to the fact that ^{241}Pu has a half-life which is much shorter than the other isotopes, it is anticipated that its decay product, ^{241}Am will also be present at recordable values.

8.7   When the analysing laboratory reports radionuclides which are members of a natural decay chain there are two questions that should be asked.

♦   Are these radionuclides naturally occurring in the waste or material?

♦   Does the presence of a particular radionuclide imply the presence of other recordable radionuclides which may not be directly measurable?

8.8   Because naturally occurring radioactive species are present in the environment, it is not unusual that these radionuclides may be reported in samples of materials such as soil, clay, brickwork etc. The objectives of the fingerprinting exercise, and the history of the waste or material should be borne in mind in order to decide whether these natural series radionuclides are reportable. If it can be shown that certain naturally occurring radionuclides are present at comparable activities in similar uncontaminated materials, it may be reasonable to omit them from the fingerprint. Any decision to omit naturally occurring radionuclides from a fingerprint should be justified. Sampling uncontaminated materials in order to establish baseline levels of these radionuclides may strengthen the case for their omission from a fingerprint.

8.9   If the history of the waste or material indicates contamination with uranium, radium or thorium (or any of their decay products), the relevant natural series radionuclides should be recorded in the fingerprint. Caution is advised, however, when disregarding any naturally occurring radionuclide, and particularly isotopes of uranium, radium or thorium for the purpose of developing a fingerprint. If the analysis results suggest uranium or thorium at enhanced levels it would be inappropriate to simply fail to account for them in the fingerprint. In circumstances where the fingerprint is intended to support nuclear material accountancy in addition to Clearance and Exemption, these radioelements should not be omitted from the fingerprint.

8.10   It should be assumed that uranium from artificial sources has been chemically separated from its natural series decay products, and only those with relatively short half-lives will be present in equilibrium with the head of chain. That is, in the case of the ^{238}U decay chain, the activities of ^{234}Th, ^{234m}Pa and ^{234}U are assumed to be equal to ^{238}U. Unless there is evidence of ^{230}Th or later decay products the decay products further down the chain should be ignored for the purpose of

developing the fingerprint. In the case of ^{235}U, the activities of ^{231}Th, and ^{231}Pa are assumed to be equal to ^{235}U. In the absence of evidence of ^{227}Ac or later decay products the decay products further down the chain should not feature in the fingerprint.

8.11   In the case of thorium, near equilibrium conditions are reached with all members of its decay chain within a period of around 30 years. The time since chemical purification of thorium is an essential input to determining the relative activities of its decay products. In the absence of information regarding the age of thorium it should be assumed that ^{232}Th has already achieved equilibrium with all of its decay products. Note that the branching ratio for production of ^{208}Tl means that its activity will always be 0.36 times that of all higher radionuclides in the ^{232}Th decay chain.

8.12   The presence of certain naturally occurring radionuclides may be taken to imply other radionuclides higher in the same decay chain. This is important, since often a particular radionuclide of interest may not easily be measured directly. A good example of this is ^{238}U which emits only very low energy gamma rays with poor probability so is unlikely to be measured directly by gamma spectrometry. However, the meta stable state of ^{234m}Pa, which is in equilibrium with ^{238}U, emits a high energy gamma which is easily measured using gamma spectrometry. Where the half-life of a naturally occurring radionuclide is relatively short (that is, the half-life is less than or equal to one third times the age of the waste or material since equilibrium conditions with its parent were last altered) it should be assumed that it is in equilibrium with its parent.

8.13   Where the measured radionuclide is a decay product of radon or radon itself, it is reasonable to question whether there may be any loss of radon gas from the material which has gone undetected. If this is the case it would imply that the activity of radon and or higher members of the relevant decay chain may be greater than the reported activity of radon and its subsequent decay products.

8.14   Towards the end of the decay chains of uranium, radium and thorium, each radionuclide has a short half-life (note that half-lives for ^{210}Pb and ^{210}Po exceed 3 months and as such are reportable to the Low Level Waste Repository Ltd, LLWR Ltd, if waste is to be disposed to the Low Level Waste Repository, LLWR). It is reasonable to expect that there is equilibrium between these radionuclides. The history of the waste should provide some indication what type of radioactive material to expect and will guide the process of inferring higher chain radionuclides (e.g. uranium, thorium and ^{226}Ra).

8.15   Similar considerations may be drawn for artificial radionuclides which are part of a non-natural decay chain, however the degree of equilibrium between artificial radionuclides (e.g. ^{241}Am and ^{241}Pu) may not be obvious and therefore direct measurements of artificial radionuclides, where possible, are preferred.

8.16   The presence of artificial radionuclides may suggest the presence of other radionuclides due to similarities in the mode of production and distribution within the waste or material. For example, ^{137}Cs often implies the presence of ^{90}Sr, another fission product. ^{60}Co may imply the presence of other activation products such as ^{63}Ni and ^{55}Fe. The history of the waste or material, and any chemical or physical processes which may have affected the mixture of radionuclides anticipated in the fingerprint should be considered.

8.17   Ensuring that additional sample material is available allows for the possibility of further analysis if the results are at all unusual. Under these circumstances the credibility of the analytical data will be further enhanced by having different laboratories performing duplicate analysis.

10   Fingerprints

9.1   A radionuclide fingerprint is an estimate of the anticipated radionuclide mix present on or in an article or substance, and is often referred to when producing an activity assessment during the characterisation of radioactive substances. This Chapter describes the recommended process for developing, documenting, implementing and maintaining radionuclide fingerprints, hereafter referred to as fingerprints.

10.1 Regulatory Framework for 'Out of Scope' Materials

9.2   The Exemptions Provisions Documents limit the specific activity of specified radionuclides in materials which are outside of the scope of regulation as radioactive substances. Provided the specific activity of a named radionuclide present in a material does not exceed the stated limit, and provided that there are no other radionuclides present, the material falls out of the scope of regulation. The 'out of scope' limits specified in the Exemption Provisions Documents reflect the relative radiotoxicity of the radionuclides. Those radionuclides which are difficult to measure because they have low energy or low probability emissions generally have higher 'out of scope' limits.

9.3   Radioactive substances seldom contain single radionuclides however, and so the Exemptions Provisions Documents include a Sum of Quotients (SoQ) rule in order to simplify the process of assessing materials with mixtures of radionuclides. For materials containing a mixture of radionuclides in fixed proportions, the limit on specific activity is calculated as the inverse of the sum of each radionuclide's activity divided by the proscribed limit for the particular radionuclide. Effectively:

$100 / (\Sigma_1^n X_i / Y_i)$

Where X is the specific activity of each radionuclide in the mixture; and,
Y is the corresponding exclusion limit.

When percentages of radionuclides are used, the inverse sum is multiplied by 100, as in the equation above.

Table 9.1   Illustrative derivation of an exclusion limit

Radionuclide	Percentage of total activity	EPR Limit $(Bq\ g^{-1})$	Activity / EPR Limit	Exclusion Limit $(Bq\ g^{-1})^a$
^{137}Cs	20	1	20/1 = 20	20/262 = 0.08
^{238}Pu	1	0.1	1/0.1 = 10	10/262 = 0.04
^{239}Pu	3	0.1	3/0.1 = 30	30/262 = 0.11
^{240}Pu	4	0.1	4/0.1 = 40	40/262 = 0.15
^{241}Pu	62	1	62/1 = 62	62/262 = 0.23
^{241}Am	10	0.1	10/0.1 = 100	100/262 = 0.38
Total	**100**		**262**	**0.88**

9.4   Consider, for example, a material whose radioactivity comprises, say, 10% cobalt-60 (^{60}Co), 5% iron-55 (^{55}Fe) and 85% nickel-63 (^{63}Ni). In this case, the maximum specific activity that may be regarded as out of scope of regulation is:

$100 / [(10/0.1) + (5/100) + (85/100)] = 0.99\ Bq\ g^{-1}$

Note that in the above example the maximum out of scope specific activity for ^{60}Co is $10*0.99/100 = 0.099\ Bq\ g^{-1}$ which is very close to the prescribed sentencing limit for pure ^{60}Co, demonstrating that the other radionuclides have very little effect on this limit.

9.5   Even though the limit on a key radionuclide may be relatively low (in the above example, the specific activity limit for ^{60}Co is 0.1 Bq g^{-1}) the presence of other radionuclides with higher limits may lead to a higher overall sentencing activity concentration the the previous SoLA value of 0.4 Bq g^{-1}.

10.2 Fingerprint Application

9.6   The intended purpose of the fingerprint should be carefully considered at the outset in order to determine the range of radionuclides and the level of accuracy with which they require to be reported. For radioactive waste fingerprints, typical applications will always include Transport and Dose Assessment in addition to Waste Disposal. Nuclear Material Accountancy may be another application, depending on the site where the material originated and the nature of the material.

9.7   It is important that each of the intended applications is carefully considered, when preparing fingerprints in order to ensure that radionuclides which are required to be reported in the final activity assessment are not overlooked. In order to clear materials from regulatory control all radionuclides need to be considered, but the sentencing limits set for certain radionuclides within the Exemption Provisions Documents already allow for activities of specified progeny radionuclides, and there is no need to double-account for these. The principle is the same for transport purposes but the reference values and implied progeny radionuclides are not necessarily the same, as those specified in the Exemptions Provisions Document*. Different waste receiving organisations tend to specify different rules for which radionuclides are reportable. All of this implies a degree of flexibility in the way the fingerprint is applied. For example, if waste is going to be characterised to determine whether individual sentencing volumes are outside of the scope of regulation or not, it may be prudent to prepare two versions of the same fingerprint which reflect the different reporting requirements.

10.3 Background

9.8   The major volumes of radioactive materials or wastes generated on nuclear sites contain a mixture of radionuclides, which contribute to the total activity of the material or waste in question. The ease with which these different radionuclides may be detected and quantified depends upon the type of radiation they emit, the energy of their radiation, the potential for absorption of radiation within the types of articles or substances present and a host of environmental and practical considerations.

9.9   It is common practice within the nuclear industry to establish approximate ratios of radionuclides within the radioactive material in order to facilitate later assessment of the activity within discrete articles or substances. A comprehensive list of the radionuclides that are likely to be present in the waste or material, and their relative contributions to the total activity, is commonly known as a *fingerprint*. An illustrative fingerprint is presented in Table 9.2 below. Note that the precision with which the results are quoted is far better than any credible measurement uncertainty and is used, in this illustration, to make the sum = 1.

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*   For transport purposes, certain radionuclides may be omitted from the fingerprint on the basis that their half-lives are reasonably short (less than 10 days), and they are only present as a result of the radioactive decay of a different radionuclide that is already accounted for. For nuclear material accountancy, there is no *de-minimis* level for recording.

Table 9.2   Illustrative fingerprint

Alpha-emitting radionuclides	Percentage of total activity	Beta-emitting radionuclides	Percentage of total activity
^{238}Pu	1.82	^{241}Pu	45.0
^{239}Pu	1.37	^{137}Cs	27.0
^{240}Pu	2.39	^{90}Sr	10.0
^{241}Am	2.80	^{147}Pm	3.64
^{242}Cm	0.08	^{154}Eu	1.09
^{244}Cm	0.64	^{155}Eu	1.09
		^{151}Sm	1.18
		^{134}Cs	0.99
		^{60}Co	0.91
Alpha	9.1	Beta	90.9
Alpha:Beta ratio: 1:10			
Reference Date: XXXXX			
Reference Number: BXXX/FP/999			

9.10   Fingerprints are used to infer the activities of radionuclides that cannot be conveniently measured directly, based on information about the radionuclides potentially present. Provided it is valid to establish and use fingerprints in support of overall activity assessments, their application simplifies the process of classifying wastes or materials. Requirements for detailed monitoring and/or analysis will be less intensive since application of fingerprints avoids the need to independently measure all radionuclides in each volume of radioactive material sentenced. Thus, the time and cost associated with characterisation will be reduced.

10.4 Requirements

9.11   Within a fingerprint, those radioactive species that are relatively easy to quantify are termed 'key radionuclides'. In common practice, species such as ^{137}Cs, ^{60}Co or ^{90}Sr+^{90}Y which emit radiation with moderate to high energy are often regarded as key radionuclides, and may easily be measured using non-destructive techniques such as dose-rate monitoring, contamination monitoring or, in the case of ^{60}Co and ^{137}Cs, gamma spectrometry.

9.12   There are certain pre-conditions that must be fulfilled in order to apply a fingerprint. Broadly, these are:

♦   there must be at least one key radionuclide present; and,

♦   key radionuclides must be present in relatively fixed proportions to the other radionuclides.

9.13   If there is more than one key radionuclide present, and if their relative activities are fairly constant, it is possible to infer the activities of all other radionuclides based on the combined activities of the key radionuclides. It becomes easier to check the validity of the fingerprint if there is more than one key radionuclide present, since they may be measured independently and their activities may be compared with each other.   This is an especially useful approach where, for example, contamination is a mixture of fission and activation products. Cs-137 will represent the fission contribution and Co-60 the activation. This does not necessarily imply that activities of all other radionuclides in the fingerprint do not vary, and depending on circumstances, it may be appropriate to do further tests from time to time to assess the entire fingerprint to ensure that gradual 'drift' away from the original relative activity contributions does not occur.

9.14   For the purpose of sentencing materials as excluded it is essential to assess the sensitivity of the sentencing limit, with regard to the variability of radionuclide ratios (see Section 10.5).

9.15   The process of assessing the activities of all radioactive species present in the material of interest is greatly simplified by measuring the key radionuclides only, and inferring the activities of all other species by cross-referencing the measured activities against the relevant fingerprint.

9.16   Fingerprints may be used to infer the activities of all radionuclides anticipated within the radioactive material, or they may be applied to a sub-set of the radionuclides. Where fingerprints are applied to infer the activities of a limited set of all remaining radionuclides in the radioactive material, these radionuclides must be clearly defined within the scope of the fingerprint and all other types of activity must be measured using other means.

10.5 Fingerprint Determination

9.17   Fingerprints may be determined from the following sources of information:

♦   provenance;

♦   radiochemical analysis of representative samples of the radioactive material;

♦   modelling codes; and/or,

♦   non-destructive assay results; or,

♦   any combination of the above.

9.18   Without exception, when determining any fingerprint it is necessary to review the operational history of the radioactive materials, noting possible contamination mechanisms, the nature of radioactivity that might therefore be present and the physical distribution of this activity.

9.19   If it can be shown that sources of contamination were fairly limited and tend to be well-defined, it may be possible to develop a fingerprint from reference to historical records such as the radioactive species handled in connection with the materials to be characterised. While historical records may provide a strong indication of the type of radionuclides which are present in the fingerprint, in certain circumstances their relative activities may continue to be unknown without further investigation.

9.20   It should not be assumed that the most recent history of the radioactive material is the only factor to be considered. Historical operations may also have contributed to the contamination within the overall volume of waste or material to be characterised.

9.21   Where contamination is strongly linked to irradiated fuel or non-fuel materials, modelling codes such as FISPACT [1], FISPIN [2, as updated] or ORIGEN [3] may be used to predict the relative activities of radionuclides produced as a result of the irradiation of nuclear fuel in a neutron flux. However, in order for modelling codes to be useful, parameters which could critically affect the quality of their output must be known with confidence. These parameters include:

♦   the physical composition of the fuel and its cladding (dimensions, materials etc);

♦   the isotopic composition of the fuel prior to irradiation;

♦   the length of time the fuel resided in a reactor;

♦   the neutron flux that the fuel was subjected to; and,

♦   the time since removal of the fuel from the reactor.

9.22   Fingerprints derived from historical records or modelling codes should be verified by comparison with real data obtained for the radioactive material itself. Ideally, this would be achieved through non-destructive *in-situ* measurements or radiochemical analysis of sub-samples of the radioactive material. These approaches allow all or some of the radionuclides in the waste or material to be quantified independently. It is recognised that it is not always possible to undertake direct measurements (e.g. because of concerns with accessibility) therefore any fingerprints that are accepted in the absence of comprehensive independent measurements should be documented in writing (see Section 10.6).

9.23   Fingerprints are most commonly developed by referring to the analytical results of samples of the radioactive material. The range of radionuclides that will require to be analysed should be guided by the provenance of the material. Failure to analyse the material of interest appropriately may mean that potentially important radioactive species are not detected.

9.24   Whereas the location of sampling points for the purpose of determining a fingerprint may be guided by provenance, the initial number of samples that should be acquired is largely subjective. Depending on the application of the fingerprint, it may be paramount to show that the radionuclides encountered are consistent, and that there is stability in either the relative proportions of these radionuclides or the 'out of scope' limit. If initial sample analyses indicate unacceptable variability, it may be important to re-zone the area of interest and take further samples. There may be more than one fingerprint or there may be just a random selection of radionuclides whose relative proportions cannot be predicted (i.e. no fingerprint).

9.25   In order to show that a material is 'out of scope', sensitivity in the calculated 'out of scope' sentencing limit is actually more important than establishing fixed proportions of predictable radionuclides with high confidence. Where multiple samples have been analysed, sensitivity analysis may easily be carried out by calculating an exclusion limit based on the analytical results for each sample, as if each sample represented a unique fingerprint.

9.26   For the percentages of radionuclides displayed in the table above, the exclusion limit is calculated as 0.38 Bq g^{-1} total activity using the equation presented in paragraph 9.3. Individual radionuclide exclusion limits are simply the total exclusion limit multiplied by the percentage of each radionuclide in the fingerprint. The values in column 4 indicate each radionuclide's influence on the exclusion limit, and varying the percentages in column 2 demonstrates that in this case the exclusion limit is most sensitive to variations in the ^{241}Am activity as a function of its low 'out of scope' limit and considerable percentage activity. Halving the ^{137}Cs activity has much less effect on the exclusion limit than a similar change in the ^{241}Am activity.

9.27   Assuming that the fingerprint presented in Table 9.2 is representative, then determining that ^{137}Cs, as a key radionuclide, is present at less than 0.08 Bq g^{-1} implies that all radionuclides will be present at activity concentrations below the overall 'sum of fractions' exclusion limit.

9.28   If the data in Table 9.2 represented one of a series of similar samples, where the percentage contribution of each radionuclide varied slightly between samples we could calculate the exclusion limit for each sample and derive a scatter diagram such as the one below.

Figure 9.1   Illustrative distribution of derived exclusion limits
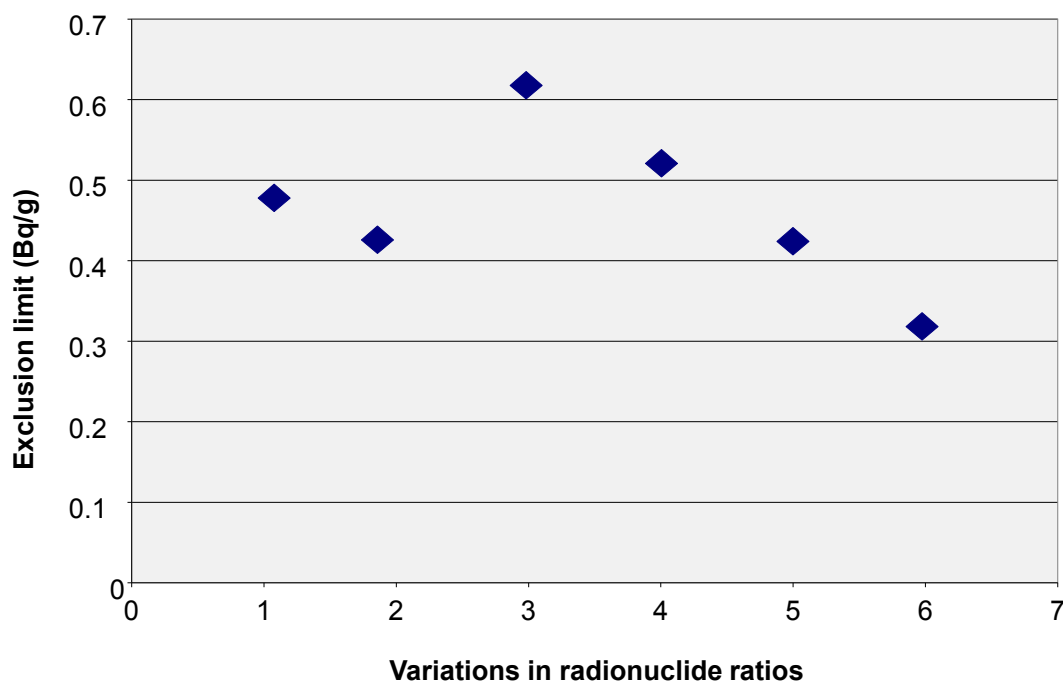
9.29   In this case, the distribution of exclusion limits is not widely spaced, and there is no reason to believe that we might have more than one fingerprint (refer to para 9.22). We need to select one of these samples as representing the final fingerprint that will be used for sentencing purposes.

9.30   All fingerprints are an approximation of the true ratios of radionuclides within each sentencing volume, and there will always be an uncertainty associated with the use of a fingerprint. It is acceptable practice to base a fingerprint upon the results for a sample that yields a low exclusion limit, and ignore the uncertainty in the fingerprint for sentencing purposes. Alternatively, a sample with a non-pessimistic exclusion limit may be used provided the sentencing decision allows for variation in the true ratio of radionuclides within each sentencing volume (for example, by selecting a sample with a near average exclusion limit; calculating the standard deviation of exclusion limits for the population of samples; and including this standard deviation in the total uncertainty for the measurement technique applied to sentencing volumes). Samples taken for fingerprinting purposes must be representative of the nature of the activity in the material to be sentenced, and therefore the quality of the sampling work is critical.

9.31   Where it is not possible to refer to radionuclide ratios for a range of similar samples, it is acceptable to notionally vary the ratios of radionuclides in the fingerprint to assess variability, and base a similar sensitivity analysis on this approach. For example, in the case of activity confined to a layer of paint, the sampling regime may well comprise collecting numerous paint scrapings, batching them together and homogenising then submitting for analysis. In this case there may be no justification for analysing additional samples, and so the information is limited to one sample only.

10.6 Documentation

9.32   Where fingerprints have been developed, they should be formally recorded along with the following information:

- the reference date at which the fingerprint is assumed to be correct;

- any information used to predict the range and distribution of radionuclides;

- the means used to plan and produce the fingerprints;

- any assumptions made (e.g. regarding homogeneity of the distribution of activity);

- how the data have been processed to derive the fingerprint (e.g. any averaging calculations);

- any mitigating circumstances which limited further efforts to define the fingerprint;

- the precise scope of the fingerprint (e.g. geometric area or zone of a facility);

- specific sources of information such as measurement instruments or key radionuclides of interest that must be used for comparison with the fingerprint during characterisation of individual sentencing volumes, if relevant; and,

- any limitations of the fingerprint which mean that full characterisation cannot be carried out from reference to the fingerprint alone.

9.33 Ideally, a common system for recording fingerprints should be implemented, and fingerprints should be uniquely identified (e.g. by the use of a systematic numbering system). Anyone reviewing and/or approving fingerprints should be demonstrably suitably qualified and experienced. Ideally there should be a measure of independence between the management organisation or persons that require characterisation of the materials, and the personnel approving fingerprints for routine use. However it is recognised that this may not always be possible for small organisations.

9.34 It is not necessary to replicate information in other sources therefore Sampling Plans, Laboratory Analysis Reports, Facility Records of Operations etc may be referenced within each fingerprint reference document provided they are officially published elsewhere. It is strongly recommended that the fingerprints and supporting information in the bulleted list above should be published in the same document.

9.35 Where fingerprints have been entered into measurement instruments in order to produce an automated full activity assessment for discrete sentencing volumes, a record verifying the correct performance of the fingerprint must be retained. This recommendation also applies to spreadsheets or other means used to automatically calculate full radionuclide-specific activity assessments on the basis of pre-programmed fingerprint information.

10.7 Implementation

9.36 Fingerprints which have been approved and assigned a unique identification number are incorporated within the responsible management organisation's characterisation strategy.

9.37 Fingerprints should be reviewed regularly to ensure they remain fit for purpose. Characterisation strategies should be designed such that it is possible to acquire information about applicable fingerprints. For example, gamma spectrometry may allow the relative activities of gamma-emitting species in the fingerprint to be compared. Cruder measurements using, say, Health Physics instruments may allow confirmation of the relative activities of alpha or beta-emitting species.

9.38 Fingerprints are subject to change. It is essential that everyone involved in managing radioactive materials which are characterised from reference to a fingerprint appreciates the need to notify their management of any obvious changes in the material, as these may indicate a change to the fingerprint which prompts further investigation. For example, a Health Physics surveyor should notice if the alpha count-rate increases relative to the beta count-rate, or engineering staff involved in

an excavation should notice if the material being excavated appears to be a different colour. As a point of principle, any concerns regarding the fingerprint should be brought forward to the person or organisation with responsibility for sentencing. Any decisions made on the basis of reviewing the information should be documented.

10.8 Maintenance

9.39   Regular review of the assessment strategy provides an opportunity to formally re-consider each fingerprint. Each review should consider the nature of operations since the characterisation strategy was previously reviewed, and the results of measurements of discrete sentencing volumes.

9.40   As a bare minimum, once a year fingerprints should be validated (for example, this may be required as a consequence of the effects of radioactive decay or the in-growth of radioactive species where the major radionuclides have half-lives of the order of a few decades or less). It is important that any decay-correction is performed on the original registered fingerprint, and not on successive annual updates. This approach minimises the effect of rounding errors. Decay-corrected fingerprints should be clearly identifiable in order to avoid using out-of-date fingerprints.

9.41   Ingrowth may also be relevant for higher actinides (e.g. ^{241}Am from the decay of ^{241}Pu).

9.42   Fingerprints should be reviewed more frequently where there is a reasonable suspicion that the nature of the radioactive material has changed significantly. This may, for example, be due to a fundamental change in a waste-generating process, or other evidence such as gamma spectrometry results which indicate a shift in the relative activities of radionuclides. In such circumstances it may be appropriate to reassess the material.

10.9 References

1   RA Forrest, 'FISPACT-2007: User manual', UKAEA, FUS534, 2007. EASY Documentation Series. Available from: http://www.ccfe.ac.uk/assets/Documents/UKAEA-FUS-534FINAL.pdf

2   RF Burstall, 'FISPIN - A computer code for nuclide inventory calculations', ND-R-328(R), 1979. Available from: http://www.oecd-nea.org/tools/abstract/detail/nea-0706/

3   Isotope Generation and Depletion Code Matrix Exponential Method. CCC-0371 ORIGEN-2.2. Available from: http://www.oecd-nea.org/tools/abstract/detail/ccc-0371

11   Statistical Basis for Sentencing

10.1   Radiological sentencing requires a consistent, agreed analytical process, set down in guidelines, to form a basis for complying with the clearance and exemptions legislation. However, the complex nature of radioactive material and the breadth of material types, sizes, and situations that may be encountered, makes sampling material and the forming of accurate conclusions about sentencing a challenge.

10.2   One approach to sentencing relies on the use of instrumentation to produce real-time data over 100% of the material. In practice, 100% monitoring is based on discrete but closely spaced readings that cover the entire area or mass of material. This is only possible where the radionuclides are detectable by suitable instruments and the mass or area of the material is accessible to the instrumentation in use. There are often situations where full monitoring is not achievable or practicable. These involve materials or items:

   ♦ that have a complex and extensive shape, or comprise a mass of heterogeneous material where activity within the body of the mass is not detectable at the surface, or

   ♦ where the radioactivity is not detectable by surface monitoring equipment, for example alpha emitters beneath paint.

10.3   In the case of either of the above, two alternative approaches may be followed:

   ♦ if access to, or the amount of, the material is the problem, monitoring may be focused on a specific number of locations in or on the material (noting that a distinction in strategy may be made where measurements are undertaken for fingerprinting or to determine specific activity in order to make decisions against an action limit), or

   ♦ if the ability to detect the radionuclides is the problem, a discrete number of samples may be taken to a laboratory for analysis.

10.4   As any method of sampling from a population requires using the sample data to estimate the true population value, there is a need to assess how good any estimate is and to determine the risk that is being taken of making the wrong decision based on the sample taken. Statistical methods can be applied to determine this.

10.5   Statistical methods need to be applied to both the approach to defining the data collection strategy **and** to the interpretation of data flowing from the subsequent analysis of the data. This chapter defines how a reasonable approach to data collection and assessment may be taken, depending on the particular circumstances of the source of contamination and the materials to be sentenced.

10.6   The approach given in this chapter relates primarily to solids. Sampling of liquids and gases does not normally need a statistical approach to be taken because, provided that the material has been appropriately zoned and homogenised where necessary, a single sample should be representative of the volume as a whole.

10.7   For the purposes of this Chapter, and as noted in the glossary, the term "monitoring" refers to the collection of data by instrumentation on a continuous basis. "Sampling" refers to collection of data either by taking a discrete number of data points from material using monitoring equipment, or by taking samples of material for laboratory analysis and subsequent generation of results.

The sampling process, the number of samples taken, the information gathered, any analysis that is done, and the reasoning behind the decisions taken at each step, must all be properly recorded for collation into an overall justification for the final sentencing decision made.

11.1 Hypotheses

10.8 The sentencing guidelines in this chapter implement a reliable and robust statistical approach, with sampling methods and analysis that generate correct results with a specified level of confidence. The approach should be implemented when 100% monitoring is not possible. The approach is based around a process referred to as hypothesis testing.

10.9 A hypothesis is a supposition that you wish to gather evidence against in order to make an informed decision. An example hypothesis might be: "The sample is radioactive".

10.10 In statistical terms, the hypothesis being tested is called the null hypothesis (often written as H_0), and the converse to that is called the Alternative hypothesis (usually written as H_1). So following on the example you might have:

H_0: The sample is radioactive

H_1: The sample is not radioactive

10.11 Developing these hypotheses further into something measurable gives:

H_0: The sample is radioactive i.e. the average activity from the sample (μ) $\geq$ limit value (Z_T)

H_1: The sample is not radioactive i.e. $\mu < Z_T$

10.12 The default null hypothesis should be that the material exceeds the sentencing limit and should be regarded as radioactive.

10.13 The statistical method of hypothesis testing provides a framework for examining the evidence before choosing a course of action while understanding the confidence you have in your decision. This measure of confidence gives you an understanding of the risk you are taking of making the wrong decision. It is important to note that hypothesis testing can only give you a measure of confidence – it cannot prove definitively either that your null or alternative hypotheses are true or false. However it does enable you to take an informed decision.

10.14 For any hypothesis test there are two different types of error that can be made. Table 10.1 outlines these errors in the context of sampling to test for radioactivity.

Table 10.1   Errors in Hypothesis Testing

		Findings from Hypothesis Test	
		Reject H_0 sample mean < Z_T	Accept H_0 sample mean $\geq$ Z_T, or < Z_T
Reality	Material has average activity $\geq Z_T$	Type 1 error (False negative)	No Error
	Material has average activity < Z_T	No Error	Type 2 error (False positive)

10.15 There is a relationship between the two types of errors and the number of sampling points taken (the sample size). The risk of a Type 1 error can be fixed but the risk of a Type 2 error is more difficult to calculate, although it can be estimated. Due to this, it is important to ensure that your null hypothesis is defined so that the risk of the error you are more concerned about is fixed.

10.16 In the case of radiological sampling, it is assumed that the risk of identifying a sample as not being radioactive when it is (false negative), is a worse case than identifying a sample as being radioactive when it is not (false positive). Therefore, the

hypotheses should be defined to ensure that the Type 1 error (false negative) should represent the worst case, and therefore take the following form:

Null hypothesis, H_0 $\qquad\qquad$ $\mu \geq Z_T$

Alternative hypothesis, H_1 $\qquad$ $\mu < Z_T$

11.2 P-values and Significance

10.17 Statistical tests examine the data which have been gathered and assess whether these data provide evidence which supports the null hypothesis or not. This assessment is carried out by making the assumption that the null hypothesis is true and will only be rejected in favour of the alternative hypothesis if there is strong evidence for doing so.

10.18 It is possible to calculate a probability that the data which has been gathered could have been observed if the null hypothesis was true. This probability calculation is effectively quantifying the "what are the chances of that" question which arises when people look at data.

10.19 This probability value is called a p-value. The p-value is the probability that if the null hypothesis was true you could still have observed the sample data which you have. So for example, take the following hypotheses for alpha values from soil:

H_0: $\mu_a \geq 1.1$ Bq g^{-1} ; H_1: $\mu_a < 1.1$ Bq g^{-1}

10.20 If sampling data shows an average value of 0.8 Bq g^{-1} then this appears at first glance to be consistent with the alternative hypothesis. However as this is a value which has been taken from just a sample of the whole area of interest, there is necessarily uncertainty as to how accurate this value is. It is possible that the sample has by chance been taken from areas where the alpha levels are low and a different sample might have produced a higher average. The p-value will give you the probability that if the null hypothesis was true how likely it would be to obtain a sample with an average alpha value of 0.8 Bq g^{-1} just by chance alone.

10.21 Therefore, the p-value gives you a quantification of how likely it is that your sample may be appearing non-radioactive purely by chance, not due to the actual condition of the material.

10.22 Once the p-value has been obtained, the judgement needs to be made about whether to accept or reject your Null hypothesis.

10.23 This judgement is based on a pre-defined significance level, which can be interpreted as the risk of rejecting the null hypothesis when it is true, i.e. the risk of sentencing material as out of scope when it is in fact radioactive, or of failing to take remedial action when needed. This significance level is often referred to in statistical terms as alpha. Due to potential confusion for two different meanings of alpha in this document, it will be referred to as the significance level throughout.

10.24 The significance level sets the accepted risk of a type 1 error (i.e. a false negative). The confidence is 1-significance which is the confidence we have that, if H_0 is true, it will not be rejected. That is, the confidence that hazardous material will not be incorrectly sentenced. The principle of p-values and significance level is demonstrated in Figure 10.1.

Figure 10.1   Significance level definition

Range of possible p-values

0   0.2   0.4   0.6   0.8   1

Reject null
hypothesis

Accept null
hypothesis

Point at which you decide to reject the null hypothesis
is when:

P-value < significance level

Depends on the level of risk you are willing to take of a
Type 1 error.
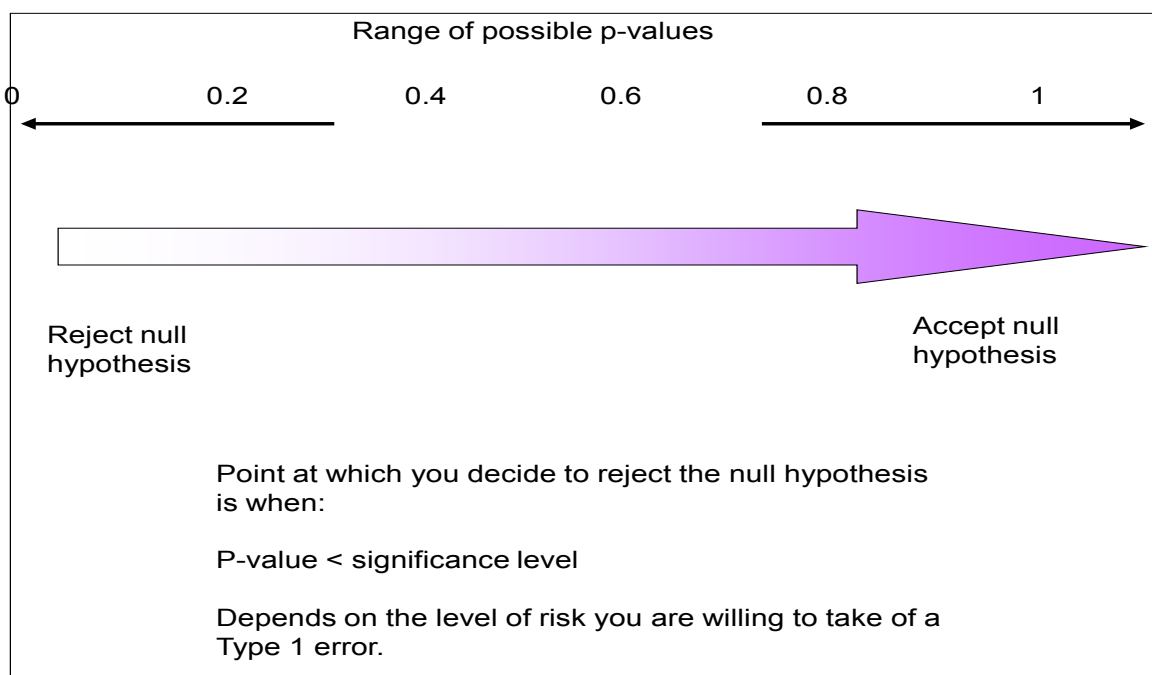
10.25   The significance level should be set according to the guidance in Appendix A (usually 5%).

10.26   The mechanics of carrying out a hypothesis test are outlined in Section 11.4 using an example carried out in statistical software. Statistical tests can be carried out by hand. However it is recommended that whenever possible statistics software is used to carry out hypothesis testing. Use of software is recommended because it reduces the risk of computation error, is much quicker to do and good software can also help the user make sure they are using the correct test.

11.3   The sentencing process

11.3.1 Scoping & pre-characterisation

10.27   Review all existing knowledge of the article or substance to be sampled. Of particular interest are the results of any previous sampling or monitoring of the material that can be used to determine if any additional pre-characterisation samples would be of benefit.

10.28   Where there is no prior information on the activity concentration, some preliminary **random** sampling will need to be undertaken to provide data on which to base the process.

11.3.2 Determine sampling objectives

10.29   In addition to the generic sampling principles given in Section 7, other specific objectives may be needed taking into account the provenance of the materials. These may include, but are not necessarily limited to:

♦   What restrictions, if any, are imposed by the volume of the material? For example, will the material need to be segmented into batches?

♦ Are there any technical considerations, such as the composition of materials and the potential for early segregation or zoning (these will affect the assessment methods and costs)?

♦ What are the logistical implications in conducting sampling? For example, storage constraints pending the outcome of testing (once sentenced, any possibility of further contamination or activation must be prevented).

♦ What are the desired time scales for completion of the sentencing process (these may dictate the sampling methods available)?

♦ Identify the most cost effective methods of sampling, measurement and disposal of materials.

10.30 As an example, the above considerations may highlight constraints on time, which may affect decisions about whether to adopt a phased sampling analysis approach. A single round of analysis may be quicker than a multi-stage analysis, but is not necessarily the most cost-effective way to sentence materials.

11.3.3 Characterise expected distribution

10.31 Use the prior knowledge referred to in step 1 in Figure 7.1 to make a judgement about the possible distribution of contamination within each zone. This is necessary to determine which statistical test and sampling approach is initially used. This assumption is then reviewed following step 7 in Figure 7.1.

10.32 The approach used in this Good Practice Guide is based on two classes of heterogeneity which are given and described below.

10.33 <u>Class 1</u>: The activity exhibits a symmetric distribution of sample values. This could have arisen from a diffuse source of contamination that has impacted the whole zone, for example a contaminated suspension. This is illustrated in Figure 10.2. A common symmetric distribution is a normal or Gaussian distribution.
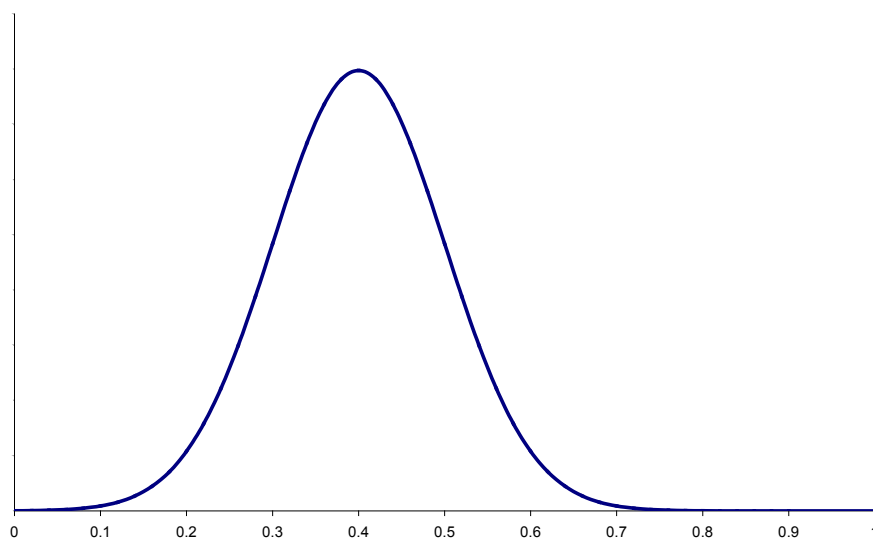
Figure 10.2 Example of a symmetric distribution of activity

10.34 <u>Class 2:</u> The activity exhibits a <u>skewed or asymmetric distribution</u> of sample values. This could have arisen from a diffuse source of contamination that has impacted only a proportion of the mass or area of material, for example walls in buildings where tritium is processed. This is illustrated in Figure 10.3.
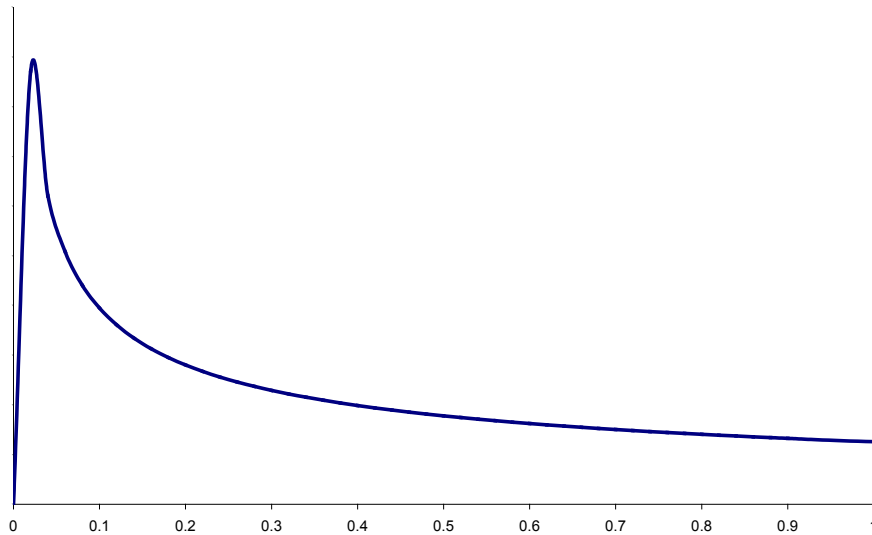
Figure 10.3 Example of an asymmetric or skewed distribution of activity

10.35 Appendix D Table D.1 gives everyday examples of materials and the class of distribution in which they are likely to belong.

10.36 Skewed data can be transformed to make it symmetrical. Common transformations are square root, log and inverse. For example, if activity has a skewed distribution, ln(activity) will often be symmetric. It is important to remember that the sentencing or clearance value, as well as all the sample values must be transformed in the same way. For example the mean of the logged values would be compared to the $\ln(Z_T)$*. This is equivalent to comparing the geometric mean of the samples to the sentencing or clearance value. An example is given in section 11.4.

10.37 There may be circumstances where the contamination of the article or substance in question does not immediately fall into one or other of the distributions given above. A simple example might be where an area of land with a broadly low level of activity present, but with a number of areas having higher activities. Such a distribution would be multi-modal, as shown in Figure 10.4.

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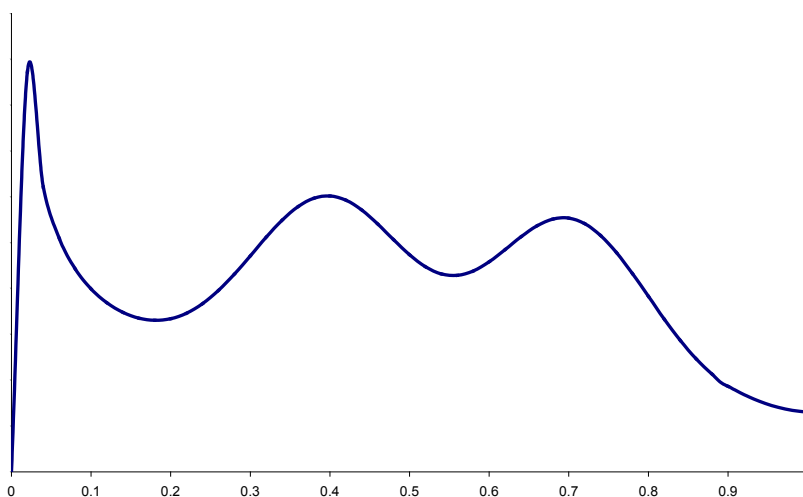
*   The mean of the logged values will not be equal to the log of the mean of the original values.

Figure 10.4 Example of a multi-modal distribution

10.38 There are also other types of distribution. Use of an alternative distribution is not advisable and professional statistical advice should be sought when there is a need to consider alternatives. Multimodal contamination should be zoned or 'mechanically' divided (for example by stripping off layers of vegetation that might have enhanced levels of activity, or by use of decontamination techniques) so that the activity in the rezoned or mechanically separated materials follows either of the two basic distributions identified above.

11.3.4 Define sampling requirements

10.39 In order to determine the sample size required, there are a number of factors which needed to be chosen or calculated:

acceptable Type 1 error rate (sig level) i.e. the maximum chance of a false negative;

acceptable Type 2 error rate (β) i.e. the maximum chance of a false positive;

an estimate of the likely standard deviation of the data*;

the size of difference which sampling needs to be able to detect.

10.40 The size of difference is the precision required for the sampling. For example, take an area of interest where the true average alpha value is 0.8 Bq g^{-1}. The area can only be sampled to estimate this alpha value as the whole area cannot be sampled. How far from 0.8 Bq g^{-1} could the sample estimate deviate and still provide a useful estimate? If, for a true average value of 0.8 an acceptable estimate would be between 0.7 and 0.9 then the size of difference (precision) would be 0.1. In reality the true alpha value is always unknown; however the size of difference or precision required of the estimate has to be chosen to enable the appropriate sample size to be calculated.

10.41 Standard statistical software will perform the sample size calculation taking these values as inputs. To carry out the calculation manually see appendix D.1.4.

10.42 Where it is expected that a transformation is likely to be needed, the sample size calculations should use the standard deviation of the transformed prior/preliminary data, and a transformed size of difference (see appendix D.1.4).

10.43 Where there is a limit on the number of samples which can be taken, it is possible to then estimate the likely Type 2 error rate, therefore assessing the level of risk being taken by using that number of samples (see appendix D.1.4).

11.3.5 Set significance levels

10.44 Set the significance level (what probability of a Type 1 error is acceptable risk). This should be taken to be 5% unless circumstances suggest otherwise (see Appendix D for further discussion).

10.45 It is not possible to fix the Type 2 error – this can only be estimated and is dependent on the significance level, the sample size you take and the variability between samples. However, when the sample size is fixed, estimating the Type 2 error

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*   If available this can be estimated from previous similar data. There is no set limit on the number of samples needed to estimate the standard deviation. However, sample size estimate will only be as good as the assumptions put into the calculation. Therefore, if you have a lot of data with which to estimate the standard deviation, you will be more sure about your sample size estimate. If it is based on a small number of data its worth calculating the sample size for a range of standard deviation to see how sensitive the overall calculation is to your estimate of sigma.

allows some quantification of the level of risk being taken with that sample size. Appendix D.1.4 gives an example of this.

11.3.6 Define sampling zones

10.46   Consider zoning the article or substance to facilitate the statistical assessment of its properties and the nature and type of contamination.

Zoning should be used wherever it is reasonable to do so.

10.47   Different zones will be independently sampled and sentenced in a way that reflects the nature of the material and/or the perceived level, nature and type of contamination of the zone in question, and hence the sentencing decision. Redefinition of zones may occur at other stages in the overall process, or between stages, as more information leads to a better understanding of the article or substance under consideration.   Figure 10.5 sets out the method of deciding whether zoning is appropriate.

10.48   The concept of a zone is not just geographical.   Within a discrete piece of the material to be sentenced there may be different zones depending on how it is intended to be processed.

Figure 10.5   Flowchart for deciding zones
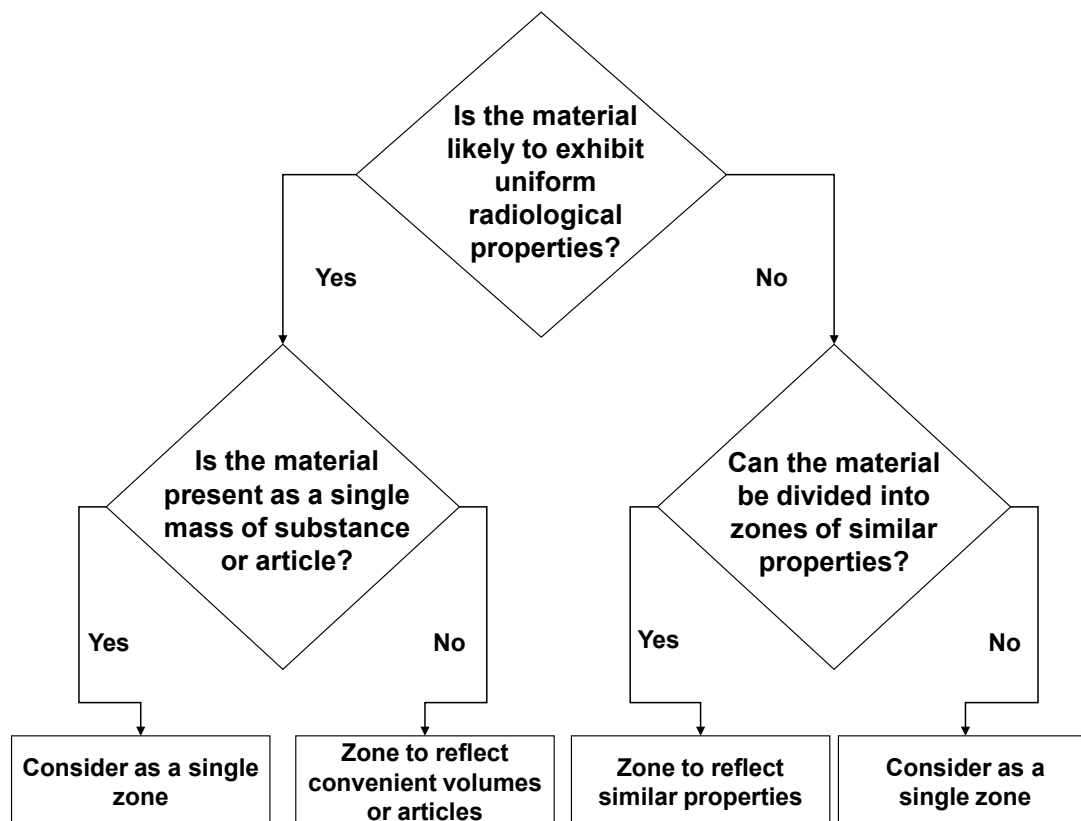
11.3.7 Collect data

10.49   When physically taking samples, a fundamental requirement of the application of statistical tests is that the data should be unbiased, i.e. the sampling pattern must be truly random.

10.50   If bias is introduced into sampling (for example by taking samples only from those locations where direct measurement shows elevated activity) then the outcome of a statistical test will be compromised.

10.51 Square grid patterns or herringbone patterns are both permissible approaches to taking samples. Where contamination is not elongate in shape and aligned in the direction of the grid, square grid sampling is sufficient to meet most sampling requirements, and is relatively simple to set out. In other situations, herringbone pattern approaches should be used, see section D.1.1. It may be appropriate to zone the perimeter separately. A regular pattern should not be used where there is potential periodic contamination across the area, in these cases, a random jitter (offsetting points randomly) should be applied to each sampling point.

Whatever sampling pattern is finally selected, an unbiased (random) starting point located anywhere within the area MUST be used.

10.52 In cases where a large volume of material is to be sampled, it is permissible to consider this as a stack of layers, each of which can be divided up into a grid and sampled accordingly. If this approach is taken, then each layer must be considered as a separate zone with a thickness appropriate to the potential inhomogeneity.

10.53 Other measurements (or making reference to the previously determined nuclide fingerprint) may be used to support the analysis of the material, provided that sufficient data are available from which to estimate the association between the surrogate measurement and the activity of the sample. Section 8 gives relevant information on this topic.

10.54 If good quality data already exists (e.g. from randomly selected samples), from which the activity levels can be derived, these can be used provided that use of the data can be properly justified and that the justification is recorded as part of the documentation.

10.55 A fuller discussion of the approach to collection of samples in an unbiased manner is included in Appendix D.1.1.

11.3.8 Verify assumptions

10.56 Histograms are a very useful way of representing the distribution of the values of the data*. The data are collated or binned† into ranges and the numbers of data points in the range (scaled by the total number of data values for the frequency plot) are plotted as vertical bars against the ranges. The shape of the data distribution is made apparent by these plots. The sample data gathered should be plotted as a histogram to determine if the initial assumption about distribution was correct. If the shape confirms the initial judgment, then the most appropriate statistical test can be chosen as described in Figure 10.6 .

10.57 Plotting of histograms can also help to identify whether there are any outliers in the data. If there appears to be any outliers the reason for this should be established. If the outlier is genuine, then the material may need further zoning to home in on specific hotspot(s) represented by the outlier(s). If the outlier has resulted from analytical or measurement error, then the result may reasonably be ignored. An example of identifying outliers, is described in Section 11.4.

10.58 It is important to recognise that some of the techniques for visualisation of data can be misleading. The selection of bin sizes (i.e. how many ranges to divide the data into) when constructing histograms should be undertaken with care to avoid

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* These can be easily done in Excel via the Excel Add in: "Analysis ToolPak" (then accessed through the Tools menu and Data Analysis option).

† Binning data is dividing it into categories where each category is a range e.g. if you had discrete data which lay in the range of 1-20, it could be binned into 4 ranges: 1-5; 6-10; 11-15; 16-20.

masking trends in data. General guidance would be to set the bin size as 10% of the appropriate limit.

10.59 Scatterplots (see Figure 10.7 for an example) are also a useful means of exploring the data and can highlight both outliers and also if there does not appear to be much uniformity in the sample area. In this case, the sampling zones may then need to be redefined.

10.60 There are statistical tests for identifying outliers which most statistical software will provide. However these can be quite conservative. If in doubt as to whether to remove an outlier from the dataset or not it is worth carrying out the analysis both with and without the outlier present to see how influential it is to the results.

11.3.9 Apply tests & sentence

10.61 Figure 10.6 gives a flowchart of the analysis process. Some worked examples follow in Section 11.4.

Figure 10.6 Flowchart of analysis process*

```
┌─────────────────────┐
│  Calculate the      │
│  number of samples  │
│  needed and collect │
│  data               │
└─────────────────────┘
          │
          ▼
┌─────────────────────┐
│  Plot data and deal │
│  with any outliers  │
└─────────────────────┘
          │
          ▼
┌─────────────────────┐        No      ┌─────────────────────┐
│  Are data distributed│──────────────▶│  Transform data with│
│  symmetrically?     │                │  a suitable function│
└─────────────────────┘                │  f(x)               │
          │ Yes                        └─────────────────────┘
          ▼                                      │
┌─────────────────────┐        No                │
│  Are the data or the│◀─────────────────────────┘
│  transformed data   │
│  normally           │
│  distributed?       │
└─────────────────────┘
          │ Yes
          ▼
┌─────────────────────┐                ┌─────────────────────┐
│  Carry out a t-test │                │  Carry out a Wilcoxon│
│  on the symmetric   │                │  signed ranks test on│
│  data, with         │                │  the symmetric data, │
│  hypotheses:        │                │  with hypotheses:   │
│  H0: μ ≥ ZT (or     │                │  H0: μ ≥ ZT (or     │
│  f(ZT))             │                │  f(ZT))             │
│  H1: μ  ZT (or      │                │  H1: μ  ZT (or      │
│  f(ZT))             │                │  f(ZT))             │
└─────────────────────┘                └─────────────────────┘
          │                                      │
          │                                      ▼
          │                            ┌─────────────────────┐
          └───────────────────────────▶│  Is p-value <       │
                                       │  significance level?│
                                       │  i.e. statistically │
                                       │  significant?       │
                                       └─────────────────────┘
                                    Yes │              │ No
                                        ▼              ▼
                              ┌──────────────┐  ┌──────────────┐
                              │  Sentence as │  │  Sentence as │
                              │  exempt      │  │  radioactive │
                              └──────────────┘  └──────────────┘
```

Carry out a t-test on the symmetric data, with hypotheses:
$H_0: \mu \geq Z_T$ (or $f(Z_T)$)
$H_1: \mu \ Z_T$ (or $f(Z_T)$)

Carry out a Wilcoxon signed ranks test on the symmetric data, with hypotheses:
$H_0: \mu \geq Z_T$ (or $f(Z_T)$)
$H_1: \mu \ Z_T$ (or $f(Z_T)$)

11.3.10   Document process

10.62 Recording of the following must have been undertaken throughout the process:

♦ all of the data gathered and used;

♦ the reasons for the decisions made at each stage; and

♦ the outcome of the analysis

10.63 All of these records should now be collated and stored appropriately in accordance with the other requirements in this Good Practice Guide.

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*   It is important to note the difference here between this method via computer and carrying out the tests by hand. When done manually, you work out calculated t or w and then compare to a critical value found by looking up a table which gives you the appropriate value for your chosen significance level. Which is greater determines whether to reject or accept your null hypothesis. The software does the same calculations but then outputs the probability that the data you have could have been observed if the null hypothesis is true. So this gives you more information than doing it manually. This is because you know also whether to reject or accept the null hypothesis by comparing p-value against significance, like comparing t against the critical value but you also with the probability figure have a quantification of the risk of wrongly rejecting the null hypothesis. Regardless, software should be used for hypothesis testing for the reasons outlined previously.

11.4 The sentencing process

11.4.1 Example 1

10.64   Data was taken from soil and gross alpha and beta activity levels recorded for 915 sample points. The soil has a natural background activity level of 0.7 Bq g^{-1} for alpha activity and 0.6 Bq g^{-1} for beta activity. Given that standard limits for non-natural radioactivity is 0.4 Bq g^{-1} the two hypotheses which will be tested are:

H_0: $\mu_a \geq$ 1.1 Bq g^{-1} ; H_1: $\mu_a <$ 1.1 Bq g^{-1}

H_0: $\mu_b \geq$ 1.0 Bq g^{-1} ; H_1: $\mu_b <$ 1.0 Bq g^{-1}

10.65   Figure 10.7 gives a scatter plot of alpha levels versus beta levels. Figure 10.8 presents plotted histograms of the alpha and beta activity levels. The alpha activity appears to have an outlier which may be distorting the distribution of the data, and also contains a negative value, which was removed in the scatterplot. The beta level activity looks reasonably skewed. Other methods of exploratory data analysis are given in Appendix D, Sections D.1.2 and D.1.3.

Figure 10.7   Scatterplot of alpha and beta activity
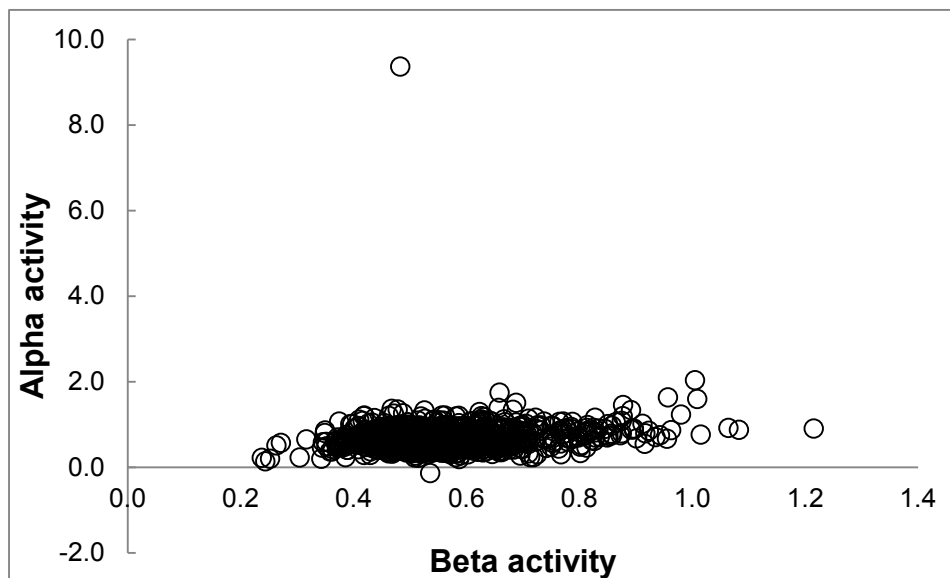
Figure 10.8   Histograms of alpha and beta activity
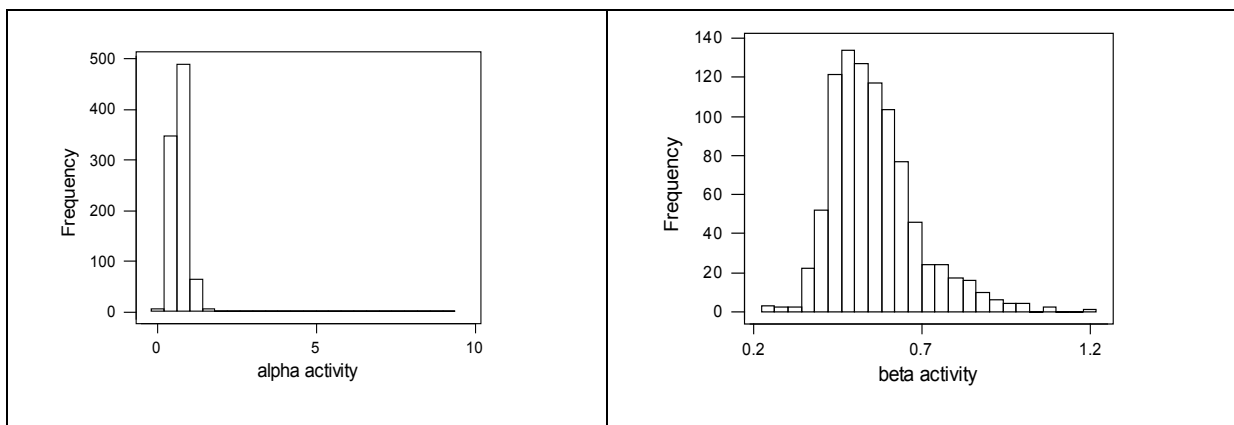
10.66   Further investigation of the outlier value in the alpha activity would need to be conducted to determine whether it was a genuine value. For the purposes of illustrating the statistical methods, this analysis will assume it is not a genuine value and will be conducted with it removed.

10.67   Both the alpha and beta activity levels show evidence of being asymmetric or non-normal distributions. Symmetry is one of the assumptions you have to make to use the statistical tests outlined earlier. One option for addressing this is to transform the data (i.e. take the log or square root of all the data points) as often if data isn't symmetric, sometimes the log or square root or some other transform of the data is symmetric. Then the test can be carried out on the transformed data as the assumption of symmetry is then reasonable.*

10.68   The alpha values, with outlier removed when the square root is taken of the data now appears to have a symmetric or normal distribution† as illustrated in Figure 10.9.‡

Figure 10.9   Histogram of alpha activity without the outlier value
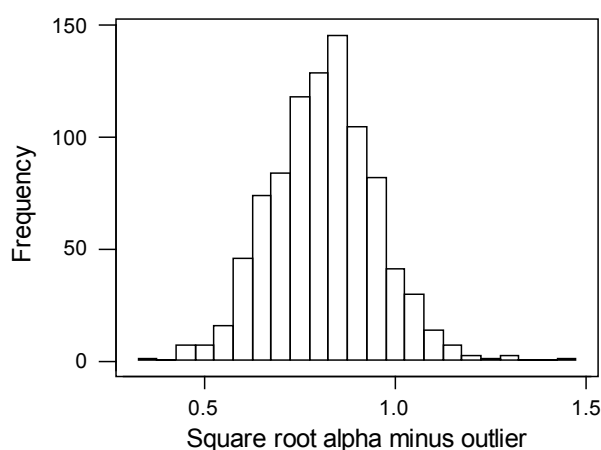
10.69   Figure 10.10 shows that a log transformation for the beta activity levels gave a symmetrical, but non-normal distribution.

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*   Using this approach, the key thing to be careful of is interpreting the numerical output from the test as it will all be on the square root or log scale. However, if to assess whether to accept or reject your null hypothesis you can use the p-value of the output of testing on the transformed data without having to interpret the other values.

†   There are statistical methods which test for normality, for example the Anderson-Darling test. However, these tests can be quite conservative, so plotting and visualising the data is often the best way to judge the normality of the data.

‡   As the outlier has been removed, the rest of the data is not as bunched up (i.e. the scale on the original graph goes from 0-10, the scale on the graph of the transformed data with outlier removed goes from 0-1.5). By presenting the data minus one outlier value you can see more granularity of the rest of the data.

Figure 10.10 Histogram of log beta activity levels
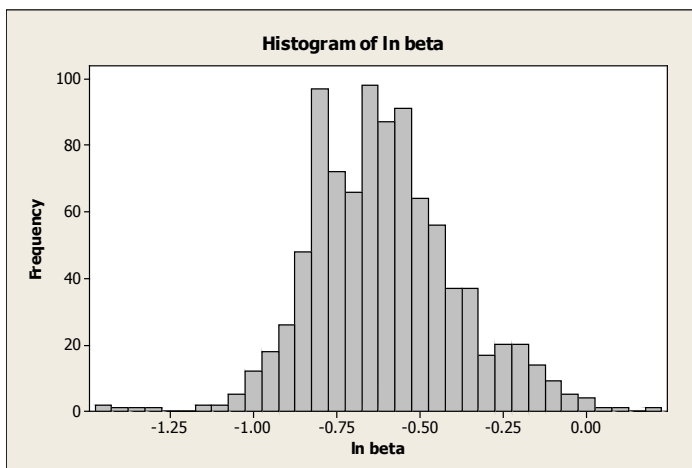
10.70 Therefore a t-test will be carried out for the transformed alpha levels and a Wilcoxon signed rank test for the transformed beta levels. Both these tests will output a p-value.

10.71 The Wilcoxon test compares the median of the data as opposed to the mean. The threshold is logged, to match the data. The output from this test, carried out in statistical software is given in Table 10.2.

Table 10.2   Output of Wilcoxon test on beta activity levels

Test of median = 0 ln (Bq g^{-1}) versus median < 0 ln (Bq g^{-1})				
Beta Activity	Sample Size	Wilcoxon Statistic	P-value	Estimated Median
	915	68	0.000	-0.6148

10.72 The p-value for this test is <0.001. This is clearly below the significance level of 0.05 (5%) and hence there is strong evidence to reject the null hypothesis in this case and conclude that the sample is not radioactive in terms of beta levels.

10.73 As the test for alpha levels is being carried out on the square root of the data, the hypotheses need to be redefined as:

$$H_0: \mu_a \geq \sqrt{1.1 Bq/g} \quad ; H_1: \mu_a < \sqrt{1.1 Bq/g}$$

Table 10.3   Output of t-test on alpha activity level (minus outlier)

Test of mean ≥ 1.04881 sqrt(Bq g^{-1}) versus mean < 1.04881sqrt(Bq g^{-1})						
Alpha activity	Sample Size	Mean	Standard Deviation	SE mean	T*	P-value
	913	0.813076	0.137220	0.004541	-51.91	0

10.74 The p-value for this test is <0.001. This is clearly below the significance level of 0.05 (5%) and hence there is strong evidence to reject the null hypothesis in this case and conclude that the sample is not radioactive in terms of alpha levels.

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*   This value comes out negative as the software used subtracts the threshold from the mean rather than the other way round than is given in the appendix. It doesn't matter which way you do it as long as the rejection criteria takes into account whether you are working with negative values. Both ways of carrying out the test can be seen in different statistical textbooks and are equivalent. The important thing is though it doesn't matter what way round the calculation is done, as long as you are using the right rejection criteria or preferably using p-values calculated by software.

11.4.2 Example 2

10.75 The above example has considered alpha and beta levels separately. To consider the two together, the alpha and beta levels were added together for the 915 sample points. The soil has a natural background activity level of 0.7Bq g^{-1} for alpha activity and 0.6 Bq g^{-1} for beta activity. So this gives a combined background of 1.3 Bq g^{-1}. Given that standard limits for non-natural radioactivity is 0.4 Bq g^{-1} the hypotheses which will be tested is:

H_0: $\mu \geq 1.7$ Bq g^{-1} ; H_1: $\mu < 1.7$ Bq g^{-1}

10.76 Figure 10.11 gives a histogram of the combined alpha and beta value with the earlier identified outlier value removed. These data appear non-symmetric, so a square root transformation was applied to the data as given in Figure 10.12.

Figure 10.11 Histogram of alpha+beta levels without the outlier value
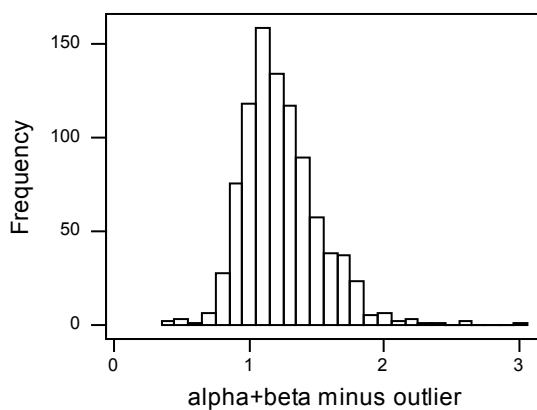
Figure 10.12 Histogram of the square root of the alpha+beta levels
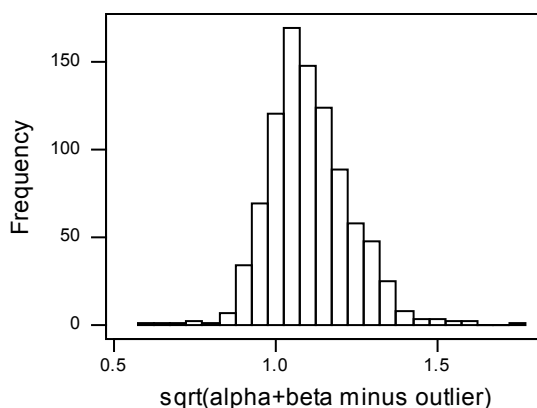
10.77 As can be seen in Figure 10.12, the square root transformation of the data appears more symmetric than the non-transformed data. However, given the long tails of the data, it still appears to be non-normal. Therefore a Wilcoxon Signed rank test was carried out on the transformed data. The results of this are given in Table 10.4.

Table 10.4   Output of Wilcoxon test on alpha+beta activity levels

Test of median $\geq$ 1.304* Sqrt(Bq g^{-1}) versus median < 1.304 Sqrt(Bq g^{-1})				
	Sample Size	Wilcoxon Statistic	P-value	Estimated Median
Beta Activity	913	8703	0.000	1.100

10.78   The p-value for this test is <0.001. This is clearly below the significance level of 0.05 (5%) and hence there is strong evidence to reject the null hypothesis in this case and conclude that the sample is not radioactive in terms of combined alpha and beta levels.

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*   1.304= $\sqrt{1.7}$ where 1.7 is the threshold that the data is being tested against.

Appendix A   Dealing with Background

A.1   Introduction

A.1   Every radiation measurement has some sort of background. When assessing the activity concentration of a material or object, we need to know the expected background so we can determine the net count signal, estimate the activity and calculate the maximum missable activity.

A.2   Sources of background

A.2   The dominant source of background signal, normally expressed in counts per second, sometimes in a defined energy range, depends on the radiation type of interest and the material being dealt with.

A.2.1 Alpha surface activity measurement

A.3   This measurement normally uses some form of large area, thin windowed detector. As alpha particles have a very high energy and a very short range, they produce very large signals in an appropriate detector. It is generally easy to set up a counting system which identifies these pulses and rejects lower energy ones generated by different radiation types.

A.4   Sources of background are:
   ♦ Contamination of the probe by the potential contaminating nuclide. This can result from poor monitoring practice, where the probe is allowed to touch the surface being monitored.

   ♦ The presence of radon wash-out. Radon progeny are washed out by rainfall. Any object which has been rained on in the previous few hours may show evidence of residual contamination.

   ♦ Radon progeny capture. Insulators can become charged and can then trap radon progeny, including alpha emitters. These can produce apparent alpha activities in the Bq cm^{-2} region. This problem can be avoided by good ventilation before monitoring

   ♦ At a trivial level, normally, natural alpha emitters within the material in question. This will be materials like concrete and granite. These can have the natural decay chains present with head of chain activities in the Bq g^{-1} region. As there are 8 alpha emitting steps in the ^{238}U chain, for example, the effective alpha activity is multiplied by, in this case, 8. The range of alpha emissions is low and only activity within approximately 2 mg cm^{-2} from the surface can be detected. As an illustration, for a uniform material with 1 Bq g^{-1} ^{238}U will produce of the order of 0.3 s^{-1} on a 100 cm^2 alpha probe.

A.2.2 Beta surface activity measurement

A.5   Again, this measurement normally uses some form of large area, thin windowed detector. Beta particles have a continuous energy distribution with a range of maximum energies, characteristic of the specific radionuclide. Beta particles generally do not deposit large energies within a detector. The very energetic ones travelling normal to the window may deposit on 50 keV, a small fraction of perhaps 2 MeV particle energy. Low energy ones at the end of their range also deposit little

energy. Hence we do not have the luxury that we had with alpha particles of setting a high energy counting threshold.

A.6　　The consequence of this is that beta radiation detectors have a much higher background. They will detect cosmic rays and environmental gamma radiation, although at a relatively low efficiency. For energetic gamma radiation, the detection efficiency is typically 0.5%.　With a typical gamma radiation dose rate of 0.02 µGy h^{-1}, approximately 120 photons are incident on the detector per second, which would give rise to 0.6 cps. In addition, there is the cosmic ray contribution. This leads to typical background count rates from beta detectors of 3 to 6 s^{-1} for a 100 cm^2 detector.

A.7　　The same factors quoted for alpha detectors also contribute:

♦ Contamination of the probe by the potential contaminating nuclide. This can result from poor monitoring practice, where the probe is allowed to touch the surface being monitored.

♦ The presence of radon wash-out. Radon progeny are washed out by rainfall. Any object which has been rained on in the previous few hours may show evidence of residual contamination.

♦ Radon progeny capture. Insulators can become charged and can then trap radon progeny, including alpha emitters. These can produce apparent alpha activities in the Bq cm^{-2} region. This problem can be avoided by good ventilation before monitoring.

A.8　　However, for beta measurement, the influence of any natural activity in the material can be much greater. The efficiency for beta detection is approximately 50% for betas incident on the detector and that for gamma radiation is typically 0.5%. Beta activity only influences the background to the depth of a few mm in most materials, whereas gamma radiation is much more penetrating. In the end, generally gamma radiation is the greater contributor.

A.9　　Natural levels of activity vary from effectively zero, from less than 1 mBq g^{-1}, up to low Bq g^{-1} for materials such as granite, sanitary ware, bricks and tiles. The latter produce obviously enhanced background counts on typical beta contamination monitors.

A.10　　There is an additional subtlety. If the background is recorded in free air, then placing substantial thicknesses of material in front of the probe will shield the background gamma radiation to some degree. For example, for clean thick steel, the background can drop by 30%. This makes it important, if the maximum missable activity is a significant fraction of the limiting activity, to have suitable background samples as references. This approach has been used particularly when making reassurance measurements on materials thought to be clean, where it is important to have a low maximum missable activity for the measurement.

A.11　　A good start is to make measurements in a low background area. Cosmic radiation is difficult to limit, although a very thick concrete roof will help considerably. Making sure any building materials have low activity is essential, with the aim being to avoid some forms of red or other brick which have high ^{40}K content, and any concrete using granite aggregate. Beyond that, the best approach is to have results from known clean materials in basically the same form.

A.12　　There is one variation to deal with beta surface activity where the background contribution from the material in question is difficult to predict. This is to make 2 measurements, one using a beta detector with an open window, i.e. a standard

measurement, and a repeat with the window covered by 3 mm of aluminium. The difference should then be calculated, and expressed as a fraction of the window covered count rate. The window covered count rate should have the free air background subtracted. Where there is surface contamination, this ratio will increase compared to normal. There are problems with this in that the statistical precision is important. Ratemeter based measurement is generally not good enough. Normally integrated counts should be used. For example, consider a detector where the free air background is 5 s^{-1}, the open window count rate is normally 12 s^{-1} and the covered is 9 s^{-1}. The difference divided by the corrected covered value is then 3/7 or 0.4. A measurement where the open value is 20 and the closed is 12 gives a net count of 8 divided by a background corrected value of 7, or approximately 1. This would be cause to treat the material as surface contaminated. On the other hand, if the open value was 16 then the ratio would be 0.6, and that might possibly just be enhanced natural, and legitimate, activity. The main problem with this approach is dealing with the statistical uncertainty in the two measurements, which will inevitably lead to a higher maximum missable activity than the same measurement on a low background material.

A.13 The same approach can be used when measuring low natural activity materials in situ where there is a significant gamma problem caused, for example, by an adjacent active building. In this case, the difference between the open and covered measurements is used to assess the contaminant activity. Inevitably, the higher the gamma dose rate, the poorer the statistical precision of any difference measurement becomes. This will inevitably lead to a higher maximum missable activity.

A.2.3 Gamma bulk activity measurements

A.14 These can be divided into two categories: one where the potential contaminant or activation product is not present in the material naturally and one where it is.

A.15 For the first case, natural activity in a material will clearly influence any gross (non energy-specific) measurement, such as gross count rate from a sodium iodide detector or count rate from a plastic scintillator based box monitor. It is important to take this into account in any maximum missable activity calculation and also to consider any likely variation in natural concentration. The best way of dealing with this is to have a known clean sample of the material. Sometimes it may be possible to buy new materials to the same specification. In other cases, it may be possible to find known clean samples of the same material elsewhere on site, such as bricks from the inside wall of a building where history shows it has always been office accommodation. These can often be checked by gamma spectrometry against possible suspect material to confirm that the naturals are at effectively the same concentrations. A doctrine of perfection is to do this on samples of building material during the construction phase with a view to dealing with the building's ultimate demolition.

A.16 There is much less of a problem where an energy selective technique is used, such as sodium iodide spectrometry. Naturals still interfere with the measurement, by increasing the background in the photopeak channel generally and interfering directly where the natural and contaminant energies are close together, such as the ^{214}Bi line at 609 keV and the 662 keV line from ^{137}Cs.

A.17 Possibly the worst example is the 185.7 keV line from ^{235}U, which is effectively inseparable from the 186.2 keV line from ^{226}Ra even with high-resolution

spectrometry. Again, calculation of the maximum missable activity will show where it would be useful to have better information on the natural content.

A.18   The second, and much more difficult, case is where the contaminant is also present naturally. Generally, this applies to potential contamination by uranium and thorium. Often, there is a partial solution, especially where the potential contaminant has been chemically separated from its decay chain. It is then possible, sometimes, to look for disequilibrium. A classic example is ^{238}U, where the gamma emissions are mainly from ^{214}Pb and ^{214}Bi which are well down the decay chain. Separated ^{238}U will rapidly reach equilibrium with ^{234}Th and ^{234m}Pa, neither of which are significant gamma emitters. However, ^{234m}Pa is an energetic beta emitter. Contamination, both surface and diffused in several mm, will show up as a high beta count rate when compared to any gamma based measurement. Similarly, contamination by ^{235}U will show up as a high 186 keV to ^{214}Bi ratio. For natural, non-enriched uranium, this ratio will be small, given the low mass fraction of ^{235}U to ^{238}U.

A.19   The other approach is basically to follow the approach proposed for gross gamma measurements earlier in that expected values are established for all the materials in question and any measurement is compared with these. This generally leads to higher maximum missable activities than simpler circumstances and again limits the ability to perform confirmation measurements on materials defined as clean.

Appendix B   The Concept of Maximum Missable Activity

B.1   Introduction

B.1   This Good Practice Guide uses the term Maximum Missable Activity (MMA) when dealing with the measurement process, as opposed to Limit of Detection (LoD). This note explains what it is and why it is used.

B.2   Limit of detection (LoD)

B.2   This term has been used for many years to describe the capacity, at the low activity end, of a measurement process. It is usually defined as the level at which a sample or measurement would be identified as not background, for a defined probability. Normally, this is calculated by determining the uncertainty in any background measurement, in terms of the expected standard deviation in the measured value, and using this to calculate an action level (i.e. the count rate which the process operator will be told to treat as indicating the potential presence of contamination). This is normally taken as the mean value plus two standard deviations. For a genuine background measurement, this will happen on only 1 occasion in 40.

B.3   On the basis of defining LoD as above, it is possible to calculate the contaminant activity that will almost always generate a count rate at or above that value. Generally, this is defined as the total count rate (background plus response to contamination) that would produce a count rate equal to or greater than the action level. This is normally defined as the mean (background + contamination) minus two standard deviations in that value. The approach by Currie [1] is generally employed. This gives an average net count rate as:

Average net count = 2.71 + 4.65 x standard deviation of the background.

B.4   This is shown in Figure B.1 overleaf.

Figure B.1.   LoD and the Derivation of Alarm Threshold Values
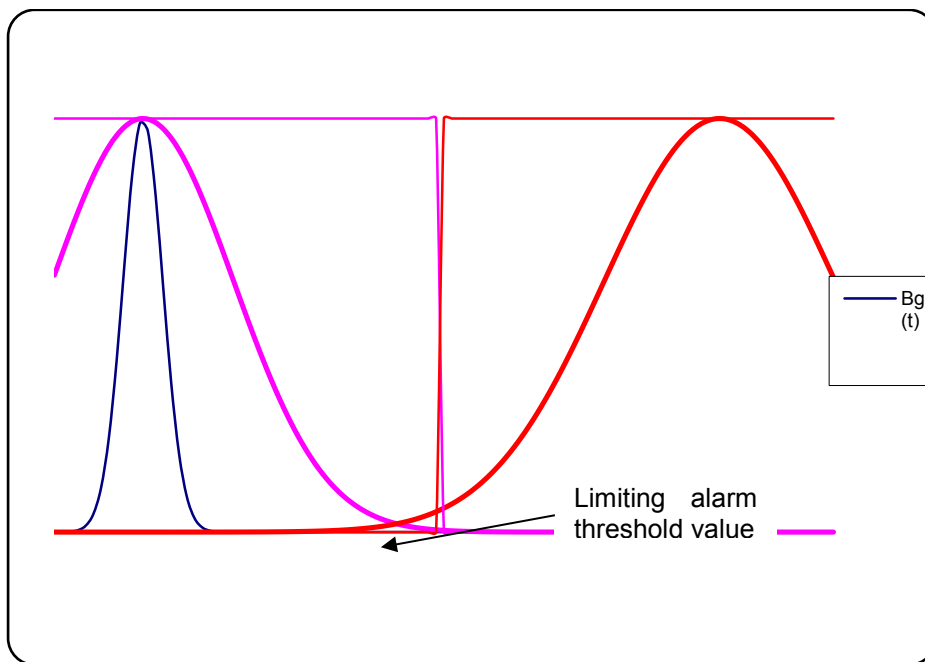
Notes:
BG(T) is the distribution calculated for a long term average.
Bg(t) is the corresponding distribution predicted for the measurement time (t) employed in practice.
Alarm is the corresponding distribution of counts from a source at the limit of detection.
The X axis is in counts per second and is purely illustrative and the Y axis is normalised probability.

B.5   This approach is very effective when looking from the top down (i.e. when the majority of measurement results are in excess of this value), but has limitations when viewed from the point of view of aiming to comply with legislation (i.e. being confident that a particular waste material complies with a legislative maximum level).   One particular problem is where the LoD is calculated, but where the monitoring process reveals values below this.   As an example, consider a box monitor where the aim is to identify hot spot activity below a defined value. If the action level is exceeded then the operator might well be asked to search for any hot spot.   This can result in the operator collecting a series of active objects some of which have activities below the limit of detection.   The extreme case may have an activity that is only a few % of the LoD.   A typical example may have an activity that is only 50% of the LoD.   Figure B.2 illustrates this.   The left hand (black) line is the expected distribution of background counts.   The right hand (red) line is the distribution of counts for a source that would give a count rate above background plus two standard deviations on 50% of occasions.   Note that for the example quoted, the box monitor, the standard deviation would be wider than shown, as we'd have to deal not only with the effect of counting statistics but also with the influence of variation in hot spot position.
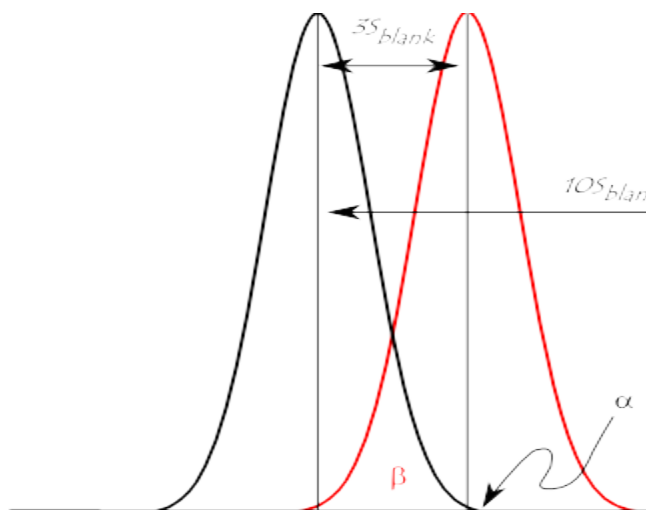
B.6   For 50% of measurements, the monitor operator will see an alarm and then search the contents and recover the object. The corresponding activity is approximately 50% of the LoD. This can be very confusing for any project manager or customer in that we quote the limit of detection as, for example, 20 kBq and then present a series of finds, some of which may be as low, or lower than, 5 kBq.

B.7   The other weakness is that, mistakenly, the LoD is often calculated on a very simplistic basis just from the expected standard deviation in a background sample. For most measurements involving the clearance process, this will give a gross under-estimate of the true value.

B.3   Maximum Missable activity (MMA)

B.8   The weaknesses described above suggested an alternative approach.

B.9   This was to encourage the use of, and calculation of, the Maximum Missable Activity. This is defined as the maximum activity that stands a defined and small chance of not being detected.

B.10   It views the process from the right side and encourages the question "What's the maximum activity that we could miss, every now and again, with this measurement". The follow on question then is "If we do miss such an activity, will we be in breach of legislation?". It also means that customers for the monitoring service, such as project managers, are not puzzled when the monitoring service reports the finding of particles below the LoD as our statement to them would be "We will virtually always find hot spots in excess of X kBq and we will sometimes find objects below that level, but increasingly less reliably as the activity reduces". **The mathematics for traditional counting is exactly the same as in the calculation of LoD.**

B.11   Another advantage is that the new approach encourages application to monitoring processes that have traditionally been much more loosely defined, such as surface contamination monitoring. Here the mathematics can be more complicated but are still consistent with LoD.   Quite often, phrases like "Nothing permitted above background" are used in the clearance of potentially surface contaminated objects. This is extraordinarily vague.   Being rigorous, something approaching 50% of measurements will be above the average indication. Obviously, this is not useful. What will be happening in the process is that the surveyor will be making some sort of judgement on what seems suspicious. For alpha monitoring, the decision on

what is suspicious is relatively simple. Normally a surveyor moves a probe at about one probe dimension per second. The surveyor normally stops when there's a beep and waits to see if there are other beeps. Hence the MMA is that activity which will almost always result in a beep. This is approximately 4 cps. This count rate can then be converted back to an MMA using the probe response in counts/s/Bq for spots or counts/s/Bq cm^{-2} for distributed activity, making allowance for the surface condition.

B.12   For beta monitoring, and the less common X and gamma monitoring, the situation is more complicated. These detectors often have significant background count rates. For a 100 cm^2 probe, the background in a concrete building can range from 3 to 10 cps. The surveyor is then confronted with the problem of identifying potential contamination against a significant, statistically varying but also sometimes position varying background. Identification is done generally by ear, as the surveyor concentrates on guiding the probe over the surface, holding the right distance and avoiding damage to the probe. Opinions on what is the maximum missable count rate vary. One approach is to consider what, on a second by second basis, would be an unusually high legitimate background. For a typical 5 cps background, 10 cps is unusual and probably identifiable by ear. The surveyor will then pause, back track a little and then see if the increase is sustained. A total of at least 10 cps would normally occur where the average value is about 18 cps. Hence, in this case, an excess leading to an average of 13 cps will normally be observed. This can be used to calculate the MMA using the instrument response to the expected fingerprint. If the MMA is well below any action level, such as the surface limit for clearance for the particular material or object, then that relatively crude calculation is sufficient. Where there is less headroom, the problem needs to be addressed more rigorously.

B.13   Such identification processes also inevitably depend on the skill and attitude of the surveyor. It is for these reasons that this document encourages the use, where appropriate, of scaler-timer based measurements, where the average count rate for a defined area is determined over a defined time. This process requires much less skill and the derivation of MMA is much easier.

B.4   Summary

B.14   The calculations are basically the same as in LoD but the concept is clearer to non-specialists in particular and encourages the view from the right direction, i.e. can we be sure to meet the limit rather than can we measure down to the limit.

B.5   Reference

1   Currie L A, Limits for the Qualitative Detection and Quantitative Determination. Application to Radiochemistry, Anal. Chem.*, 1968*, 40 (3), pp 586–593

Appendix C   Monitoring Equipment and Measurement Techniques

C.1   Bulk Alpha Monitoring

C.1   Bulk alpha monitoring is difficult without using radiochemistry. The explanation is simple. The maximum range of an alpha particle is very short, only a few microns in dense solids. For low natural activity materials, it is sometimes possible to remove a sample from a bulk material, such as soil or concrete. This is then homogenised and either counted as a very thin layer (a few microns) or as an infinitely thick layer. The first approach has the advantage of a relatively efficient sample, i.e. one in which a significant proportion of any alphas generated leaves the surface of the source. The response of an alpha detector placed directly above, and in virtual contact with, the sample can be estimated reasonably well. The disadvantage is that the mass of the very thin sample is extremely low, normally less than 0.1 g, and the maximum count rate at a limiting level of 0.4 Bq g^{-1} will be less than 1 count in 100 seconds. Counting times to get any sort of statistically credible number will be very long and significant corrections for even the very low background count rate of a well-designed and clean alpha counter will be significant. Any level of inhomogeneity will also cause major uncertainties and the mass present will have to be measured carefully.

C.2   The same detectors can also be used for a much thicker sample that removes the uncertainty associated with the mass as the thickness is in excess of the maximum range of an alpha particle, i.e. it is effectively infinitely thick. The count rate will be slightly higher but the response is more difficult to predict. The need for homogeneity is slightly reduced, but is still important. The technique can be used, for example, on a concrete surface or on a tray of soil that has been riddled to remove twigs and pebbles and then flattened.

C.3   The only reliable way of calibrating such equipment is to take a well mixed sample of the material of interest, determine the net (background corrected) count rate using the equipment described above and then determine the alpha activity of the nuclides of interest by radiochemistry. This basically involves extracting the alpha emitting nuclides from a bulk sample, concentrating them and then manufacturing an efficient source that can be counted in much the same way as described above. The net count rate from the direct counting process can then be compared with the activity of the nuclides of interest to produce a response factor. This process is described in more detail in the section on radiochemistry.

C.4   The main uses of direct bulk alpha measurement are to make regular checks on the fingerprint of materials with a significant alpha fingerprint fraction to confirm the stability of the fingerprint and to confirm the relative homogeneity of materials which only contain alpha emitters, thus limiting the number of samples required per unit mass cleared. It will not work at all well where the materials have high natural alpha activity levels, such as some soils and concrete. The detectors employed are basically the same as those used for direct surface monitoring.

C.5   Note that many alpha emitters also emit X radiation and it may be better to employ X-ray monitoring techniques.

C.2   Bulk Beta Monitoring

C.6   Direct bulk monitoring for ^{3}H and ^{63}Ni is impossible, and reliance must be placed on sampling. For other beta emitters, broadly the same restrictions apply to direct beta monitoring as for direct alpha monitoring. For low energy emitters, such as ^{14}C, the range is similar to that of an alpha particle but for high energy emitters, such as ^{234m}Pa, which is part of the ^{238}U decay chain, the range is up to 6 mm in soil or concrete. It is for these higher energy emitters that direct monitoring is possible, either in situ, on concrete surfaces or soil, or following sampling and a very limited preparation, such as riddling soil and flattening.

C.7   In the latter case, the sample thickness should be not more than 6 mm, even when high energy beta emitters are expected. This will minimise the count rate generated by natural gamma emitters in the sample.

C.8   The detectors employed are basically the same as those used for direct surface beta monitoring. The difference from alpha monitoring is that there will always be a significant background count rate, either from environmental background gamma radiation or from gamma emitters within the sample. This is why the technique only works for more energetic emitters, where the count rate per Bq per gram can be 100 times higher than the corresponding value for alpha or low energy beta emitters.

C.9   It is possible to make a reasonable estimate of a detector's response but again the best approach is to use analytical methods to determine the true activity of the contaminant and compare this value with the apparent net activity. Similarly, the main usefulness of the technique is as a part of a check on consistency of fingerprint or of the relative homogeneity of activity in identified materials.

C.10   Shielding the detector will reduce the background count rate and improve performance. Using an energy window, rather than just a simple energy threshold, may sometimes help. This should be selected by optimising the ratio of $S^2/(S + B)$, where S is the net response to activity in counts s^{-1} at the clearance level and B is the background count rate in counts s^{-1}.

C.3   Bulk Gamma Monitoring

C.11   Bulk gamma monitoring forms the basis of many clearance exercises. It can be a relatively accurate technique compared to many. The main uncertainty comes from the homogeneity (or lack thereof) of the material being assessed. Either the selected monitoring volume (drum, 1 m^3 builder's bag, loader bucket, in situ area) can be assessed directly or the volume can be sub-sampled. For full volume monitoring, good results can be produced for material such as:

♦ Brick and concrete rubble;
♦ Soil;
♦ Shredded low density metal; and
♦ Low atomic number, low density, materials generally.

C.12   An important point is that it is often necessary to have a volume of known clean material to act as a background, particularly where gross gamma or low resolution gamma spectrometry is employed. One reason is because natural activity in the material will produce a signal from the detector. Another reason, when monitoring is performed with the material in bags or drums, is that a clean sample will provide

at least partial shielding for the detector. Failure to take this point into account can lead to a clean sample apparently having negative artificial activity. For sub-sample monitoring, the accuracy is less dependent on the material and density but is much more dependent on homogeneity (or the lack thereof). The various measurement techniques are described below. In all cases, it is worth bearing in mind that doubling the detector linear dimensions will tend to reduce the time taken to monitor a particular volume of material by a factor of at least 4.

C.3.1 Monitoring using a relatively small hand-held detector and gross gamma detection

C.13   This approach generally uses a fairly simple ratemeter connected to a probe by a cable about 1 metre in length.

Detector types:

C.14   Sodium iodide scintillation detectors, plastic scintillation detectors.

Essential attributes:

C.15   The detector should have a reasonably large area and a significant probability of detecting any gamma photon that strikes it. Most popular is the 3 inch diameter, 2 inch thick, sodium iodide scintillator. Increasing the diameter reduces the maximum missable activity effectively but there is little point in increasing the thickness. Large plastic scintillators are also useful and have the advantage that for the same weight they have a larger area which will even out fluctuations due to activity inhomogeneity.

C.16   Generally, they are set up with an energy threshold of less than 60 keV. This is as much for the convenience of testing and calibration as for operational use as 241Am is the most convenient and widely available low energy (60 keV gamma) source.

C.17   The mode of operation is to hold the detector in virtual contact with the volume to be monitored and to note the count rate. **The background count rate, derived, for preference, from a known clean volume of the same material is then subtracted** and the net count rate divided by the detector response in counts per second per becquerel per gram.

C.18   Calibration is best achieved using a representative load which is contaminated to several times the acceptance limit with the appropriate nuclide mix. This is only rarely possible but can be found, for example, when decommissioning fuel cooling ponds where the surface is likely to be much more contaminated than the bulk. The average activity in a well-mixed volume can be established by gamma spectrometry and radiochemistry. This value can then be used to divide the net count rate from the normal monitor to derive a response in counts per second per Bq per gram which can, in turn, be used to calculate the acceptance limit.

C.19   Alternatively, and generally more practically, the net count rate can be calculated using a deterministic or Monte Carlo based code designed to model interactions both within the load and the detector. The accuracy of the programme can generally be checked by calculating the response to a source buried in a defined position within a load. This can then be checked by reproducing the situation with a real source and measuring the real count rate. Agreement between the calculated and experimental source will give confidence in the bulk load prediction. This

process can also be used to correct for the container thickness, e.g. the excavator bucket, when monitoring through the container wall.

C.20   A very simple method of predicting the response is to treat the source as semi-infinite and to calculate the surface dose rate. This can then be combined with the measured dose rate based on the energy response of the detector to the major gamma line to give a corresponding count rate. Generally that will give a result which is lower than the true value. Setting a limit for monitoring on that basis will mean that monitoring is conservative. This is not a problem where the material to be processed has a low natural gamma activity level and where the vast bulk is expected to be genuinely clean.

C.21   The equipment is easy to use and much tougher than surface contamination monitoring equipment. Any measurement is also derived from a significant mass of material, given the penetrating nature of gamma radiation.

Potential problems:

C.22   Lack of homogeneity can be addressed by making several measurements round the volume of interest, for example one on each side of a builder's bag and one on top, and averaging the answer. Monitoring of material in an excavator bucket can use the same approach except that measurements made through the side of the bucket will have to be corrected for the attenuation in the bucket walls, which can be up to 15 mm thick steel.

C.23   Measurements cannot be made close to edges of the load but must be made in positions where the load fills the view forward from the detector. The measurement is also potentially susceptible to either missing hot spots or overestimating the bulk activity if activity might be present in discrete pieces, such as fuel particles or radium luminised dials. In this case, it is almost always worth searching for such objects before final monitoring. The simple way to do this is to spread excavated material in a thin layer on a floor and walk over it with a sensitive gamma monitor. A better way is to pass the material in a thin layer down a conveyor belt under similar detectors fitted with an alarm. Any hot spots can then be picked out before final checking for average bulk activity. Alternatively, where multiple position measurements are made, two criteria can be set; one is that the mean count rate should be below a defined value and the other is that the maximum should be below a higher defined value. This latter approach will check that there are no hotspots in the outer layer of a bagged load but, ultimately, in any significant weight or dimension of material, there is a fraction of the material in the centre of the load which is effectively not monitored. Hence, bulk monitoring without an initial thin layer search is best applied to material which is unlikely to contain significant hotspots.

C.24   The technique is also best employed where the material to be monitored has a low natural activity or, at minimum, has a low and consistent natural activity. Problems can arise with building rubble where the natural activity per gram can vary from less than 0.1 Bq g^{-1} in flint concrete to several Bq g^{-1} in granite, tiles and glazed sanitary ware. It is important to ensure that mixed activities are not present in one bag and that the limit is adjusted for each material type to allow for the changes in background activity. For clearance where the gamma component of the fingerprint is low, it will not be possible to employ simple gross gamma monitoring techniques for materials other than those with negligible natural activity.

C.25   Measurements can often be made in ratemeter mode where the fingerprint is dominated by energetic gamma emitters and the natural activity levels are low. In this case, the background count rate will be low and the limiting count rate will be much higher. The normal approach is to calculate the net count rate corresponding to the limiting activity and add the background count rate. This then becomes the technical acceptance limit. Most programmes introduce a note of caution here and give the operator two other limits; one is significantly below that count rate and is the count rate where it is statistically unlikely that the activity exceeds the limit, allowing for reasonable measurement uncertainties, including the statistical fluctuation of the indication. The other is one above the theoretical acceptance limit where it is statistically unlikely that the material is below the limit. Material that meets the first count rate limit goes into the comply stack, material that exceeds the second value goes into the fails to comply stack and any material in between goes into a stack for further examination.

C.26   For more difficult objects, timed counts can be used. This removes the subjective nature of ratemeter measurements and allows for the statistical power of each measurement to be selected. The longer the counting time, the less the uncertainty in the final estimate of count rate. The detector does not need to be held still during this process. It can be moved over the surface to be monitored (provided it isn't taken too near the edge) and thus give an average answer for the surface. Using reasonable monitoring times of up to 60 seconds per side can reduce the maximum missable average activity by a factor of 3 compared to ratemeter measurement.

C.3.2 Monitoring using a relatively small hand-held detector and a counting window

C.27   This generally uses the same type of equipment as for gross monitoring but with the addition of an electronic energy counting window which helps to reduce background count rate.

C.28   Sodium iodide or caesium iodide scintillation detectors attached to a simple analyser with a lower and upper energy threshold.

C.29   These units use one of the types of detector and monitoring techniques as for gross gamma monitoring, except that they have an element of energy selection. This can reduce the maximum missable activity compared to the simple case, particularly for materials which naturally have significant and variable levels of gamma emitters with energies above those of the potential contaminants. ^{40}K, which is found in many minerals, is the commonest example. The usual way to employ these is to set the energy threshold (if there is only one) just above the energy of the potential contaminant. For ^{137}Cs (E = 662 keV) this would be set at about 720 keV. Counts in the top channel are unaffected by the presence of ^{137}Cs. If the material under examination is uncontaminated then the ratio of the count rate in the high channel (>720 keV) to that in the lower channel will be effectively constant and will not depend on the natural activity level.

Potential problems:

C.30   The technique cannot be used where the energy of the contaminant is close to that of the naturally present gamma emitter. Good examples are ^{60}Co as the contaminant (1.17 and 1.33 MeV) and ^{40}K as the natural nuclide (1.41 MeV). Similarly there are problems with ^{137}Cs (662 keV) and ^{214}Bi, derived from ^{238}U, which has its major line at 609 keV.

C.31   The technique also shows no advantage over gross gamma counting where the contaminant is the same nuclide or nuclides which are present in the natural activity. For example, where the natural activity is mainly the ^{238}U chain, the major gamma emitters are below ^{226}Ra. Hence the technique cannot be used where the potential contaminant is ^{226}Ra.

C.32   Compton interactions from higher energy natural activity will also contribute to the background in the counting window, increasing the maximum missable activity.

Signal processing:

C.33   The count rate in the high channel can be used to predict the count rate in the lower channel. This predicted value can be subtracted from the measured count rate in the lower channel to leave a net count produced by contamination which can be compared to the limit. The main problem with this is that both numbers have a significant statistical variation. Even for uncontaminated materials, the subtraction of one quite large number (the reference background count) from another (the observed count from the sample under examination) can give quite large positive or negative results. These some people may find difficult to accept.

C.34   The net count rate can then be compared with the value predicted from a calibration exercise similar to the process used for gross gamma measurement. Again, the best approach is to separate materials into the definitely acceptable for clearance, the definitely unacceptable and those where the uncertainty in the measurement is such that a confident decision cannot be made. This last group can then be examined more thoroughly to establish its true level.

C.3.3 Monitoring using a relatively small hand-held detector with spectrometry

C.35   This approach is a further advance on the use of an energy window, as discussed above. It offers the ability to deal with more complicated situations by producing a detailed energy spectrum which the user can interpret. Note, however, that Compton scatter in bulk samples means that the advantage to be gained will be less than might be expected.

Detector type:

C.36   Sodium iodide or caesium iodide scintillation detectors attached to a multi-channel analyser. Portable high purity or hyper-pure Germanium (hpGe) units which have much better energy resolution are being used increasingly. These are quite bulky and much more expensive than scintillators. However, development of these is being pushed along by security applications which means that they are becoming increasingly competitive.

Essential attributes:

C.37   The important characteristic of these detectors is the ability to produce a gamma spectrum measurement. The presence of a peak at a particular energy shows the

presence of a particular nuclide and the area under the peak above background can be used to determine the activity.

C.38   This process can reduce the maximum missable activity in materials with relatively high natural activities and has the advantage over the use of a simple counting window in that it can handle materials where the natural gamma emitters present are more variable, such as road tarmac. Multiple resurfacing and patching can lead to wide variation in the activity and nuclide content of tarmac. Some roadstones have high levels of potassium whereas materials such as tin slag can have a ^{226}Ra content of several Bq g^{-1}, which leads to a ^{214}Bi and ^{214}Pb level of close to the same level. These materials emit gamma radiations close to ^{60}Co for natural ^{40}K and close to ^{137}Cs for the radium progeny.

C.39   Another very obvious advantage is that the measurement will generally identify the presence of any significant gamma emitter. This can be important as, for example, it can detect the presence of unanticipated gamma emitters, such as ^{137}Cs derived from fuel failure, where only ^{60}Co from activation was expected.

Potential problems:

C.40   Sodium iodide crystals are only mediocre spectrometers in that they do not produce a very narrow spectrum for photopeak events. For example, the full width at half maximum spectrum height is about 8% of the peak energy. In the case of ^{137}Cs, there are significant numbers of counts in channels from energy 610 keV to 710 keV. One energy line from ^{214}Bi is at 609keV, which will spread up to 662 keV visibly in the absence of ^{137}Cs. Care is required to separate the signal from the two peaks.

C.41   The technique also shows no advantage over gross gamma counting where the contaminant is the same nuclide or nuclides which are present in the natural activity. For example, where the natural activity is mainly the ^{238}U chain, the major gamma emitters are below ^{226}Ra. Hence the technique cannot be used where the potential contaminant is ^{226}Ra.

C.42   Another problem is that many of the interactions from a potential contaminant do not appear in the peak channel, because they have either been scattered in the material to be assessed or are imperfectly detected in the crystal. A close study has to be made of this effect to see if using multi-channel analysis actually improves matters.

C.43   Sodium iodide detectors also have a significant temperature coefficient. This can lead to a peak energy drift of several percent over normal indoor/outdoor temperature differences. Some instruments use an in-built standardisation source, which will slightly increase the maximum missable activity compared to an equivalent unit without the source. Some use the ^{40}K peak which is generally detectable in the environment. Some use an optical system while others use electronic temperature compensation combined with regular energy calibration, generally using a small ^{137}Cs source. Whichever technique is employed, it is important that the operators follow the manufacturer's recommendations. Note that in very low background situations, such as over water, for detectors that use ^{40}K, it will be necessary to use a background source such as a brick or bag of high potash fertiliser to allow the unit to stabilise.

C.44   The spectrum from the material under examination should be measured and any peaks identified. Most instruments do this automatically and most also give a net area under the peak, which is the total number of counts in the peak above the background.   This value is then compared with the value derived from the calibration process which uses either a measurement of a real sample or a mathematically predicted value, both of which are described above.

C.3.4 Monitoring using a detector and a rotating load platform

C.45   This reduces the problem of manually monitoring a volume in sufficient detail to identify hot spots.

Detector types:

C.46   Larger scintillation detectors, hyper-pure germanium (hpGe) detectors.

Essential attributes:

C.47   This technique keeps the detector stationary and rotates the material to be assessed. There are many advantages to this. One is that the process can be made essentially automatic. Once the bag or load has been placed on the turntable, the process is started and operates in a defined and predictable way, removing the variability associated with hand held monitoring. Another is that the averaging process takes place automatically, at least in one plane.

C.48   The system can also sometimes be set up to identify a lack of uniformity in the signal from the load. The third advantage is that it allows the use of either larger scintillation detectors which would be too heavy (or too expensive) to be hand held. These will reduce the maximum missable activity compared to smaller ones at rate proportional (approximately) to the ratio of the diameters. A fourth advantage is that the detector can be collimated with heavy shielding which can reduce the background by a factor of approximately four quite easily which, in turn, will reduce the maximum missable average activity by a factor of approximately two.

C.49   For materials with complicated artificial and/or complicated natural activities, using a fixed monitor also allows the easy use of a hyper-pure germanium detector. These have a vastly improved spectral resolution (compared to scintillation detectors) of about 0.3% which allows the clear separation of gamma lines from natural emitters and contaminants but require either cooling with liquid nitrogen or electrically, both of which are inconvenient (although possible) with portable equipment.

C.50   The improved spectral resolution is particularly useful where the potential contaminating nuclide is part of the decay chain of a naturally present nuclide. For example, using the case above, where the natural nuclide is ^{238}U, the level of ^{234}Th can be measured with reasonable confidence and used to predict the level of ^{214}Bi and ^{214}Pb. These predicted values can then be subtracted from the observed peak heights and the resultant net values used to calculate the level of contaminating ^{226}Ra.

Potential problems:

C.51   There are no real problems with the use of a turntable and sodium iodide and plastic scintillators. Robust turntables are not expensive and do not represent a

large safety problem. The detector should not be exposed to vibration from the turntable.

C.52   Hyper-pure Germanium (hpGe) detectors pose no real operating problems provided cooling can be assured. The only real problem is in the interpretation of the spectra from the hpGe detectors. One is that it is difficult to separate the 185 keV line from ^{235}U and the 186 keV line from ^{226}Ra directly. The normal way of doing this is to look at other lines from ^{235}U which are present in lower numbers, such as the 142 keV line, and use this to predict the 185 keV line. The problem with this is that the lower energy line is more highly, and less predictably, attenuated than the higher line, particularly if the material being monitored has a high atomic number component. The other method is to measure the activity of the ^{226}Ra progeny and use that to predict the 186 keV line intensity.

C.53   Unfortunately, between ^{226}Ra and ^{214}Bi is Rn-222, which is a noble gas with a 3.825 day half-life. This will escape in an unpredictable way from excavated or crushed materials which, in turn, leads to difficulty in predicting the activity of its relatively short half-life progeny, ^{214}Pb and ^{214}Bi, leading in turn to a large uncertainty in the true ^{226}Ra level.

C.54   As discussed in the introduction to D7, a clean sample of the material of interest is useful to act as a background.

Signal processing:

C.55   This only really differs for the hpGe detectors. Normally, to make the best use of their enhanced spectral resolution, the multi-channel analyser uses at least 1024 and more usually 2048 or 4096 channels.

C.3.5 In-situ Ground Monitoring

C.56   In-situ monitoring is often used early in clearance projects to characterise potential surface soil contamination and to make the results available in the shape of a map. The map is then used to guide any soil removal exercise. The equipment can either be man portable or vehicle mounted.

Detector types:

C.57   Man-portable equipment generally uses medium sized (76 mm x 76 mm) sodium iodide scintillation detectors. These are about as large as can be carried comfortably for any length of time. Vehicle mounted detectors are generally bigger, up to 100 mm x 100 mm x 400 mm. There is little point going beyond this size as the ability to detect hot spots begins to fall if the detector dimensions are increased. This is because the entire detector contributes to the background count rate whereas parts of the detector which are relatively distant from the source do not add to the signal to a significant extent. Vehicles generally carry several detectors to produce a wide monitoring area.

C.58   Large volume plastic scintillators have also been employed. These have the disadvantage of poor spectral resolution. They do not, normally, show a photopeak, but it is possible to perform some analysis using the Compton edge. The ability to make use of the energy information from plastic scintillators is improving rapidly, driven mainly by security considerations.

Essential attributes:

C.59   The detectors have to be moved over the area of interest at a reasonably constant height and a reasonably constant speed in order to produce a consistent detection probability. The person guiding the detectors has also to be confident that the area of interest is being covered at the correct pitch, i.e. there are no areas left unmonitored which could compromise the survey. The data has also to be logged against position with sufficient accuracy. This is normally performed by logging the information from the radiation detectors against a reference from a Global Positioning System (GPS) unit. Normally the aim is to produce information at a 1 metre pitch.

Potential problems:

C.60   GPS systems require a good view of the sky in order to pick up the satellite signals. This means that GPS does not work in buildings, very close to buildings and under dense tree cover. There are other ranging systems, such as ultrasonic, which can be used in confined spaces. Man-portable systems are easy to move at a slow pace but this is more difficult for vehicles and it is essential that the vehicle is chosen with care. For many desired maximum missable activities for point sources or hot spots, the maximum speed will be about 1 m s^{-1}. This, in a more familiar unit, is just over 2 mph, which is below most vehicles' minimum speed i.e. the speed in the lowest gear at idling rpm. A low ground pressure may also be important for difficult conditions to avoid getting bogged down. This will require multi-axled or tracked vehicles.

C.61   Background changes are also likely, especially on a big site. These can be caused by changes in geology, the presence of roads and buildings and the influence of radiation leakage from active buildings. Collimation is not possible for man-portable units as it would be too heavy. This means that the radiation signal changes with position are more blurred than would be the case if a collimator was used.

C.62   The results are heavily biased towards the surface activity. The radiation from buried activity will be quickly attenuated by any covering. Hence, the process has to be used with care where there is any possibility that unacceptable activity has been buried by top dressing or by building floor slabs.

C.63   For units used outdoors, temperature stabilisation or correction is required.

Signal processing:

C.64   Currently, there are 2 methods in use. The older approach is to perform limited pulse height analysis. One common set-up is to have 3 channels, one from the minimum energy threshold up to the low energy side of the photopeak for the energy of interest, one encompassing the photopeak and one from the high-energy side of the photopeak upwards. In many situations, the shape of the background spectrum does not change drastically, only its intensity. The high-energy channel is unaffected by the contaminant of interest. The photopeak channel will include any full energy detection of the energy of interest and a proportion of the background radiation signal and the low energy channel will contain more of the background, Compton interactions produced within the detector by the radiation of interest and Compton scattered radiation generated in the soil etc by the contaminant.

C.65   Fairly efficient background correction is then performed by determining the photopeak to high-energy channel count rate ratio in a known uncontaminated area. During the actual survey, the high-energy channel count rate is multiplied by this

ratio and the number subtracted from the photopeak counts to remove, as far as possible, the background contribution. The low energy channel can also be corrected in the same way to leave the Compton scattered signal from the radiation of interest. The ratio of the photopeak channel to the background corrected low energy channel depends, to an extent, on the depth of burial of the contaminant.

C.66   The current state of the art is to use full spectrometry, which allows a more accurate correction for background. However, it is important to realise that the spectrum of the gamma radiation at the surface generated by a buried hot spot or from activity evenly distributed in depth has a very large Compton scattered component. This reduces the apparent advantage derived from full spectrometry significantly, as the majority of the events are not in the photopeak. The effect is even more dramatic for sources in water.

C.67   Depending on the circumstances (nuclide of interest, background level, desired maximum missable activity etc) the calculation algorithm may use corrected photopeak counts or the sum of the corrected photopeak counts and the corrected low energy channel for detection of the presence of a particle or contaminated area. Increasingly, once a possible area has been identified, an alarm is sounded, the vehicle is manoeuvred to maximise the signal and the same detectors used with full multi-channel analysis and a longer count time to produce a definite identification. The decision on when to sound the alarm has a big influence on the cost of a survey.

C.68   A low alarm level will give a low maximum missable activity but will also give more false positives and slow the process down. Once all the radiation and GPS data has been gathered, it is plotted using a Geographical Information System (GIS). Generally this uses colour coding based on count rate to produce a picture of any potential problem areas.

C.69   Measurements are typically on a 1 metre grid. Plotting the raw results will often result in areas which are hovering between one colour and another. Part of the GIS operation is to set rules for averaging over adjacent areas. It is important that these rules are set carefully, particularly when dealing with potential hot spots, otherwise it is possible to blur over a real hot spot **or to produce a display which is so speckled as to be useless.**

C.3.6 Conveyor belt monitoring

C.70   Bulk monitoring is subject to the criticism that concentrated activity (a hot spot) can be buried in the centre of the averaging volume and thus be difficult, or impossible, to detect. Conveyor belt monitoring is a way of tackling this problem.

<u>Detector types:</u>

C.71   Larger scintillation detectors, hyper-pure germanium (hpGe) detectors.

<u>Essential attributes:</u>

C.72   This technique has been mentioned above as a useful means of dealing with demolition rubble etc which potentially contains high activity particles or objects. It is, in principle, easy. The material under examination is crushed to a reproducible size and loaded into a hopper. This then feeds a conveyor belt which moves under a collimated detector. Any of the types described above can be used. If an excessive activity is observed then the conveyor can be set to stop automatically so

the area in view can be hand searched or it can be automatically diverted to feed the "non-compliant" container rather than the "compliant" container.

C.73   The material to be monitored is in a much thinner layer than for bulk monitoring. This means that the whole volume of the material is monitored fairly evenly, rather than having a strong bias towards the surface layer.

Potential problems:

C.74   Generally the technique demands several extra stages in the process compared to monitoring in a loader bucket, for example. Equipment such as conveyors and crushers require maintenance and pose their own safety hazards. There is additional noise, the potential for increased airborne dust and radioactivity levels and power consumption. The equipment is also much more expensive than that required for static monitoring. Soil is difficult, except when completely dry, as it tends to clog.

C.75   Processing large volumes of material close to the detectors can also lead to background changes. It is important that large volumes of material, whether clean or active, are not stored close to the detectors.

Signal processing:

C.76   The material to be monitored passes under the detector or detectors. An essential attribute is that any potentially unacceptable volume or object is under the detector long enough for the system to identify its presence reliably and also long enough so that normal background levels do not lead to false alarms. This speed is readily calculable. The bigger the detector and the larger the permitted averaging volume, the quicker the conveyor belt can run.

C.3.7 Box Monitors

C.77   Surrounding a volume of interest with detector in the form of a box means that a very large fraction of the radiation escaping from that volume will be detected. The external walls of the box can also be designed to provide efficient background shielding. The unit can also include a weighing machine. The weight of the sample can be used to correct for self-attenuation and also to calculate results directly in Bq g^{-1} when combined with the fingerprint.

Detector types:

C.78   Large plastic scintillation detectors.

Essential attributes:

C.79   These are monitors where the material in question is placed inside a monitor which effectively surrounds the load. In some monitors, all six sides of the monitor volume are detectors, in others only some are detectors. In any event, the design leads to a vastly increased probability of a gamma photon escaping from the load actually striking the detector. Not only is the detection probability increased but the background shielding is also greatly increased, generally using lead built into the doors, base and sides. Hence, the contribution from external background is greatly reduced, often by a factor of ten or more compared to the unshielded condition. It makes no change to the contribution from natural activity within the load, however. Hence the equipment makes a much better assessment of the number of gamma photons escaping from the load.

C.80   The size is varied to match the monitoring volume, with small monitoring volumes for small objects such as tools and plastic bags of low current electrical cable and small diameter conduit, up to large ones capable of taking a 200 litre drum or bigger. These are often equipped with a roller conveyor onto which the object is loaded, pushed into the chamber, the conveyor lowered and the door shut.

C.81   These monitors are only suitable for gamma emitters but can achieve dramatically low maximum missable activities approaching 30 Bq for small bags of cable potentially contaminated with ^{60}Co. This level is below anything which could be achievable with hand beta monitoring for distributed activity, and is comparable with the limit for a careful technician for an individual spot.

C.82   Another common material for which they are particularly suited is paper, such as old process records which have been stored technically in an active area but for which the history indicates that contamination should be zero or close to negligible. Paper is impossible to surface contamination monitor to levels suitable for unrestricted release because of its low mass per unit area. This is discussed elsewhere in this document and box monitoring is really the only practicable way of assessing it, particularly if the potential fingerprint has a low gamma to total activity ratio.

C.83   Most types use plastic scintillation detectors in the gross gamma mode. Plastic scintillators can be made in very large sizes much more cheaply than other effective gamma detectors. Some units also include a large sodium iodide scintillator to give spectrometric capability.

Potential problems:

C.84   The units, even the small ones, are very heavy and are best built up and left in one place. The background reduction relies heavily on good shielding continuity and clumsy assembly or transport can lead to shielding damage. They are best used for materials with very low natural gamma activity levels as the majority have no spectral resolution.

C.85   Even though they are very well shielded, keeping the external background relatively constant will reduce uncertainties in the final result.

C.86   The maximum mass of material to be monitored will also be limited where there is a possibility of hot spots. The dimensions of the sampling mass have to sufficiently small so that a hot spot of the maximum acceptable activity can be detected even at the centre of the mass.

Signal processing:

C.87   These are normally used in the gross gamma mode. The count from each detector is integrated for the selected counting time and compared with a previously measured background. The resultant net count is than compared with the limit derived, generally, from theory and backed up by experiment. If the level is exceeded, the alarm is shown. Some types go further and show which detector or detectors are over the limit. This allows the operator to search the load and perhaps identify and remove any contaminated object.

C.3.8 Vehicle monitors

C.88   Many sites use monitors to check on vehicles leaving the site. It is essential to appreciate that these monitors should not be used for sentencing. They are very useful as a final check to follow that there has been no failure in determining the

history of materials, that procedures have been followed correctly and that no unexpected activity has been found. Typical reasons for legitimate alarms include radium luminised instruments, radium based lightning attractors and, on occasions, steel which has been carefully monitored for surface contamination but which has unexpectedly been activated by neutrons from a reactor.

C.89   The other reason is that material may well comply with the clearance criteria adopted but may be unacceptable to recycling companies. These companies normally take a simple approach to scrap metal. That is that they will not accept scrap which sets off their vehicle monitor. Hence, it is important for the nuclear site to be able to despatch loads for recycling with a good degree of confidence that they will be accepted at the far end.

Detector type:

C.90   The detectors employed are generally large slabs of plastic scintillator up to a total of 60 kg on each side of the vehicle. These are supported on stands at about the mid height of a typical scrap load. Untreated random steel scrap has a surprisingly low density of around unity which means that the boxes in which it is transported are approximately 2.5 metres deep. The stands are generally made of thick steel, mainly to produce some back shielding. Each slab has one or two photomultipliers coupled to it.

Essential attributes:

C.91   The local background should be as low as possible. The units have limited spectral capability with older units operating purely on gross count rate above a low energy threshold. They are thus more susceptible to background interference than sodium iodide based detectors, for example. More advanced units use the Compton edge visible in plastic scintillator spectra to perform energy analysis which improves their sensitivity for many contaminants and their rejection of the natural background signal.

C.92   There is another dimension to the influence of background. This is that a vehicle carrying 20 tonnes of scrap steel will produce significant background attenuation. A clean load can depress the background by 25%. The unit makes an attempt to predict this depression while it is analysing the count rates produced as the vehicle passes between the detectors but the higher the local background the more difficult and uncertain this prediction becomes.

Potential problems:

C.93   The units work well for steel, which has a low normal activity. However, they will often alarm if asked to check material with a high level of natural activity such as red brick, granite blocks, fertiliser and ceramics.

C.94   They can only detect gamma radiation outside the vehicle and work best for sources close to one side of the load. If a shielded source is buried within a dense load, such as a set of RSJs aligned on the floor of the vehicle, then the maximum missable activity can be many orders of magnitude higher.

C.95   Another use of these units is for security applications where they are sometimes used in parallel with an X-ray system to check for areas that are very well shielded. This approach is not normally employed in the monitoring of scrap metal etc.

C.96   They may also interpret voids in a load as a potential source. The voids give much reduced local shielding and thus a peak in the count rate. See below.

Signal processing:

C.97   The area has to be sufficiently large to allow trucks to pass slowly between the detectors. The units continuously monitor the background count rate in the absence of a vehicle and thus can accommodate changes in background caused by rainfall (radon progeny washout) and site operations. The recommended speed is generally about 3 mph. It is measured using a pair of light beams which detect the arrival of the vehicle and estimate its speed. As the truck passes between the detectors, the unit records the count rate several times per second from each detector. Older units will alarm in 2 circumstances. One is when the count rate exceeds the previously measured background by a statistically significant value. This would correspond to a light weight vehicle with a source in it or to a loaded vehicle with a significant generalised activity within the load. The other is where the count rate falls as the vehicle enters, then rises and falls again before rising when the vehicle leaves. This would correspond to a source within a load of scrap. The alarm may be triggered even if the peak count rate does not reach normal background level. The same effect can also be produced by a void in the load. More sophisticated units perform limited spectrometry on the signal, which means they can identify changes in the spectral shape, rather than just the total count. This makes them more effective when dealing, for example, with potentially contaminated materials with high natural levels.

C.4   Direct Alpha Surface Monitoring

C.98   This normally uses either standard radiation protection monitoring equipment or the same ratemeter but with a larger area detector.

Detector types:

C.99   Zinc sulphide based scintillators, gas flow and gas refillable proportional counters, large area silicon diode detectors and blown ion chambers.

C.4.1 Direct probe monitoring

Essential attributes for direct probe monitoring:
   ♦   Large area, at least 100 cm^2 for clearance. This is essential to allow reasonably fast coverage of a surface at clearance levels.
   ♦   A thin window. Alphas have a very short range. The limiting window thickness is about 1 mg cm^{-2}
   ♦   Good beta and gamma rejection. Acceptable residual alpha surface activity levels are generally not more than 0.1 Bq cm^{-2}. At this level, for a 100 cm^2 detector, a typical count rate is about 2 to 3 counts per second. Any response to the all pervasive gamma radiation will produce a background count rate which completely masks the alpha signal.
   ♦   Virtually no alpha contamination of the detector. Again, any significant alpha contamination will conceal the count rate from the acceptable residual alpha surface activity level.
   ♦   The ability to be held close to, and at a consistent distance from, the surface of interest. For practical detectors the count rate can halve if the detector is moved from a 3 mm surface to detector separation to 10 mm. For clearance monitoring of

objects with flat surfaces, where the object is virtually always clean, stick-on feet on the detector are useful because they allow it to be placed directly on the surface in a fixed geometry. This increases the quality of the measurement. The feet can be replaced easily if there is any reasonable chance they have become contaminated.

Potential problems:

C.100   Some scintillator based types are very sensitive to magnetic fields.

C.101   These cannot be used on anything with a significant magnetic field such as a steel beam, many tools and some electrical equipment. As an illustration, a large screwdriver which had been magnetised to the point where it would just hold 4 normal paperclips reduced the count rate from an alpha source by a factor of 4 when held close to the source. Some manufacturers incorporate mu-metal shields as standard which greatly reduce the magnetic susceptibility of the probe. The other manufacturers can generally offer such shields as an option.

C.102   Window damage is very likely for any alpha detector. This has to be repaired before further use.

C.103   Gas refillable detectors are best regularly filled with counting gas. They do not like being brought back into service after a long period of disuse. The gas is also generally flammable.

C.104   Large area silicon diode detectors are generally very susceptible to radiofrequency and other electromagnetic interference.

Signal processing:

C.105   Ratemeter mode - In this method, the count rate is averaged over a few seconds and displayed. Interpretation of a fluctuating signal requires skill and is difficult to audit. Detection is by an audio signal, a beep for each alpha detected. The user moves the detector slowly over the surface of interest. When a significant beep rate is found, the user maximises it, watches the ratemeter for a few seconds and estimates the average.

C.106   Counter-timer mode - In this method, the detector is placed on the surface and the count rate integrated for a short, pre-determined, time. This value is generally recorded and compared with a pre-determined limiting value. The detector is then moved to the adjacent area and the process repeated. The advantage of this technique over the use of a ratemeter is that the level of skill is much less and is far easier to audit.

C.107   Use with energy windows. One of the problems with alpha monitoring is the potential for attenuation of the alphas by surface grease etc. A current development is to use conventional alpha detectors on a ratemeter with 2 counting windows. One generally has an upper threshold 4 times the lower and the other works from that higher threshold upwards. The high voltage, or the lower counting threshold, is set conventionally so that the sum of the two channels is on a plateau and the response to $^{90}Sr+^{90}Y$ beta radiation is negligible. The ratio of the two counting channels will be found to be very dependent on any covering of the activity, with the high energy/lower energy channel count rate ratio dropping rapidly with increasing cover. The results can be used in 2 ways. Either a lower limit can be set, below which the monitoring is deemed untrustworthy, or the ratio can be used to correct the total count rate.

C.4.2 Blown ion chamber alpha monitoring

C.108   This is analogous to the use of box monitors for gamma radiation monitoring in that the object of interest is placed inside a chamber.

Detector Type:

C.109   Ionisation chamber.

Essential Attributes:

C.110   This technique involves placing dust-free objects in a moving stream of air which subsequently enters an ionisation chamber. Any ions generated in the air can be collected and measured. The ion current is then a reasonable measure of the alpha activity on the object. The technique works really well for objects such as pipes with diameters in excess of 25 mm and will even work for complicated objects such as valve bodies with blind holes, provided that the air stream at some point blows directly over or onto the end of the hole.

C.111   The normal technique is to load the object into a closed space through which filtered air is sucked. The air then passes through an ion chamber and into a high efficiency particulate air (HEPA) filter to avoid any contamination being released.

C.112   The technique has a much lower beta contamination sensitivity because alpha particles deposit large amounts of energy in a few cm whereas beta particles either have a much lower average energy or have a range which is a factor of more than 100 times higher. Hence restricting the collecting volume of the machine means that the charge deposited per unit activity is much lower for betas than alphas.

Potential Problems:

C.113   Like all direct alpha monitoring, the alpha activity has to be on the surface to be detected efficiently and not concealed by paint or rust.

C.114   The object has to be reasonably dust free. Dust blown off the surface can be lead to high leakage currents from the ion chamber.

C.115   The technique does not work well for activity inside long, thin, pipes as the average charge deposited per alpha drops as the diameter decreases. This is because the path length in air decreases and much of the energy of the alpha particle is deposited in the walls of the pipe. It is very effective for scaffolding poles, for example, but far less so for pipes below about 10 mm in diameter.

C.116   It will work for some painted metal objects well but not for objects with a very high surface insulation level such as plastic. The electrostatic potentials which build up on insulating objects will tend to collect ions. In case of doubt, an alpha source can be placed on the material of interest and the current recorded and compared with the value derived from a conductive material. Alternatively, for the ultimate in credibility, a source can sometimes be manufactured using the material in question as the substrate. Anecdotal evidence has stated that good results can sometimes be obtained from objects such as broom heads with activity placed at the base of the bristles but monitoring any difficult objects would need to be justified by careful experiment.

C.117   Inside very long pipes, the air velocity tends to be low and the transit time long, which means more of the positive and negative ion-pairs will recombine, leading to a loss of signal.

Signal processing:

C.118   Unlike other alpha techniques, the signal is generally processed as a current rather than a pulse. This is collected in a multi-plate ion chamber and amplified. Generally the mean current is determined during the monitoring period, divided by a calibration factor derived from placing a source of known activity in a variety of positions on and in a test object and displayed. For monitors with a rotating table, additional information is provided by a current against time graph. A skilled operator can determine from this display whether the activity is on the outside of a valve body, for example, which is exposed constantly to the air flow, or inside the object where the air flow is periodic.

C.119   Maximum missable activity in or on a full length (6 metre) scaffolding pole can be as low as 30 Bq in good conditions.

C.4.3 Use of a Sorting Table

C.120   Instead of hand monitoring, where the detector is moved over the surface of interest, the objects can be placed on a large surface detector.

Detector type:

C.121   Thin windowed, gas flow, proportional counters.

Essential attributes:

C.122   Hand alpha monitoring is demanding, slow and repetitive. One way around this for objects which are basically thin and which cannot be placed in a blown ion-chamber monitor is the use of a sorting table. This technique works for relatively non-absorbent materials such as rubber gloves. The table is generally derived from a personnel walk-in monitor and comprises an array of thin windowed, gas flow, proportional counters protected by a grille. Objects to be monitored are placed on the table and counted for a fixed period. At the end of the period, they are turned over and the process repeated. As a variation on the technique, the objects can be passed between two position sensitive gas flow proportional counters.

Limitations:

C.123   The technique cannot achieve levels for unrestricted release for alphas and absorbent materials such as fabric coveralls because of the potential for very high levels of self-absorption within the material. It is also difficult to use for many-sided objects. For conventional counters, the signal is recorded on a detector by detector basis, which means that the count is automatically averaged over the detector area, even for objects which are much smaller than the detectors.

C.124   Even with non-absorbent materials, the technique will not work for very thin samples, simply because the bulk activity level has to be translated into a surface level. This is considered in detail elsewhere but, essentially, if the bulk activity level is 0.1 Bq g^{-1}, the total activity (sum of both sides) of a surface contaminated object must be less than 0.1/T, where T is the mass per unit area in g cm^{-2}. For a pair of thick gloves, this works out at approximately 0.005 Bq cm^{-2} on each side, assuming the inside is clean and that there is no significant absorption within the material.

This level is achievable. However, it is not achievable for a sheet of paper, where the one side limit is approximately 0.4 mBq cm^{-2}. Other methods must be used and provenance is of key importance.

Signal Processing:

C.125   For static monitors, the count rate is integrated during the counting period and compared with a background measured with the table empty. The net count rate is then compared with a limit derived from experiment.

C.126   For units with position sensitive counters and a moving belt the counts are integrated for each area as the object moves and presented to the operator on a colour display. The operator can then take out any demonstrably active object.

C.5   Direct Surface Beta Monitoring

C.127   This normally uses either standard radiation protection monitoring equipment or a standard ratemeter but with a larger area detector.

Detector types:

C.128   Large area, thin window, thin beta scintillators and large area proportional counters (Conventional GM types, either thin wall or thin window, have an inadequate area for use at low levels).

Essential Attributes:

C.129   Large area, at least 100 cm^2 for clearance. This is essential to allow reasonably fast coverage of a surface at clearance levels.

C.130   Detectors can be used hand-held or in the form of a sorting table or conveyor belt monitor, as described above for alpha monitoring. Blown ion chambers do not work well for beta contamination because of the lower energy of even energetic beta particles, combined with a longer range leading to a low fraction of the energy being deposited in the collecting volume.

C.131   A thin window. In most circumstances the bulk of the beta radiations present will have relatively low energies. A thin window is essential to allow efficient detection. Sometimes, if there is a major energetic component such as ^{90}Sr+^{90}Y, then a thicker window gives better robustness and also makes the count rate less dependent on the self-absorption within the surface of short range components. These will not get through the thicker window.

C.132   Good gamma rejection. Acceptable residual beta surface activity levels are generally not more than 0.4 Bq cm^{-2}. At this level, for a 100 cm^2 detector, a typical count rate is about 10 counts per second. Any excessive response to the all pervasive gamma radiation will produce a background count rate which completely masks the beta signal. The thinner the scintillator the better, provided it is strong enough.

C.133   Virtually no alpha or beta contamination of the detector. Any significant alpha or beta contamination will mask the count rate from the acceptable residual beta surface activity level. Note that all detectors with a response to low energy beta emitters will detect alpha activity.

C.134   The ability to be held close to, and at a consistent distance from, the surface of interest. For practical detectors the count rate for soft beta emitters such as ^{14}C can halve if the detector is moved from a 3mm surface to detector separation to 10mm. For clearance monitoring of objects with flat surfaces, where the object is virtually always clean, stick-on feet on the detector are useful and allow it to be placed directly on the surface in a fixed geometry. This improves the quality of the measurement. The feet can be replaced easily if there is any reasonable chance they have become contaminated.

C.135   If the nuclides of interest have a higher energy, e.g. ^{90}Sr+^{90}Y, the detector can be held further from the surface. For uniform contamination the count rate will not change out to a few cm. The major change is that the further from the surface the detector, the bigger the averaging area and the lower the count rate from a localised spot of contamination.

Potential problems:

C.136   Some scintillator based types are very sensitive to magnetic fields. These cannot be used on anything with significant magnetic field such as a steel beam, many tools and some electrical equipment.

C.137   Window damage is very likely for any beta detector. This has to be repaired before further use.

C.138   Gas refillable detectors are best regularly filled with counting gas. They do not like being brought back into service after a long period of disuse. The gas is also generally flammable.

Signal processing:

C.139   Processing generally follows the previous section. However, for clearance monitoring using scintillation detectors particularly, it can sometimes be possible to set a counting window, rather than just a simple threshold, particularly if relatively low beta energies are expected. The low energy threshold is set as normal, but, in addition, a high energy limit is set, using either an appropriate calibration source or a real contaminated object, which allows most of the signal from the contaminant to be detected but reduces the background count rate. This reduces the maximum missable activity.

C.140   Alternatively, the approach proposed for alpha monitoring can be used, with the low and high energy counting channels. This is useful where the contaminant is low energy, such as ^{14}C, and hence susceptible to absorption by grease, etc. It is also useful where there is any doubt as to fingerprint stability and the fingerprint has a range of beta energies. A variation in the high/low channel ratio will indicate a change in the fingerprint.

C.6   Direct Surface X and Low Energy Gamma Monitoring

C.141   This normally uses either standard radiation protection monitoring equipment or a standard ratemeter but with a larger area detector.

Detector Types:

C.142 Thin sodium iodide scintillators, thin caesium iodide scintillators, yttrium oxyorthosilicate scintillators, extended energy range beta scintillators and xenon filled proportional counters.

Essential Attributes:

C.143 In a similar way to beta monitoring, the detectors can be used hand-held or as part of sorting tables or conveyor belt monitors.

C.144 They require a reasonable area. Unlike alpha and low energy beta radiation, the effective range in air of even the lowest X-ray emitter of interest, ^{55}Fe, is several cm. Monitoring does not have to take place in contact with the surface. This reduces the number of separate measurements required to cover a given area. However, the background count rate of such detectors is generally higher per unit area than for beta detectors. Hence it is important to have a reasonably large detector area to improve detection of the radiations of interest. Perhaps counter-intuitively, increasing the response to a particular activity level and increasing the background by the same factor produces an answer of greater statistical significance for a given counting time. The variability between successive measurements on average reduces as a percentage with a higher count rate although it increases as a number of counts. Subtracting background thus gives a result which shows a smaller fractional variation on average over a number of measurements.

C.145 Popular sizes of sodium iodide and caesium iodide scintillation detector range from 32 mm diameter to 125 mm. Detector thickness is generally 2 to 3 mm. This gives a high detection efficiency for X radiation from ^{55}Fe (activated steel), plutonium and ^{241}Am and for ^{241}Am gamma radiation. For the detection of the very low energy radiation from ^{55}Fe, the window should be beryllium but for high energies thin aluminium is satisfactory. Normal beta detecting scintillators can also be used for very low energy nuclides such as ^{55}Fe (5.9 keV) provided very efficient light detection is used, together with very low noise photomultiplier tubes. These can use normal aluminised melinex windows.

Potential Problems:

C.146 Some scintillator based types are very sensitive to magnetic fields. These cannot be used on anything with significant magnetic field such as a steel beam, many tools and some electrical equipment. There is also a relatively limited set of calibration sources available which can make the prediction of the response difficult. Sodium iodide also requires careful sealing. Any pinhole will result in the growth of a yellow patch which both fails to scintillate and also absorbs a proportion of the light generated elsewhere in the scintillator.

Signal Processing:

C.147 See the previous section. For low energy X-radiation detection, the technique of using a counting window, rather than a simple threshold, is particularly useful for detectors with reasonable energy resolution such as the sodium iodide, caesium iodide and yttrium oxyorthosilicate scintillation detectors. This can be taken further into full spectrometry, particularly useful when there is the potential for Am-241 or plutonium alpha emitters. Any area which shows up as active using gross or windowed counts can be subject to spectrometry, reducing the maximum missable activity and providing potentially useful spectral information such as the L x-ray/60 keV ratio. Any variation in this will demonstrate either a change in the absorption of

the x-rays in paint, for example, or a change in the Am-241/Pu alpha emitting nuclides ratio.

C.7   Tritium Surface Activity Monitoring

It cannot be emphasised too much that the assessment of surface tritium activity is close to meaningless.

C.148   The mobility of tritium is such that it can diffuse into surfaces to depths of millimetres relatively easily. In some real cases, the concentration gradient of tritium reverses. Instead of falling with depth, as for most contaminants, it increases for a significant depth, peaks and then falls. This is common where the tritium exposure has stopped some time previously. The tritium then begins to diffuse back out of the surface, reversing the concentration gradient.

C.149   Tritium must be treated as a bulk contaminant. In painted surfaces, for example, the tritium concentration in the paint can be much higher than in the underlying concrete or brick, by up to a factor of 10. The first bulk layer is thus the paint. This topic is discussed further in bulk monitoring.

C.150   However, there have been cases where careful wiping (see below) has yielded reasonably consistent results against the activity in a paint layer. If there is a large area of painted surface to be assessed, it may well be worth taking a series of wipes and adjacent samples from areas where the paint is the same and comparing the two sets. If the results are reasonably consistent, wiping will enable a much bigger fraction of the surface of interest to be assessed than sampling followed by radiochemistry.

C.8   Surface Monitoring by Wipe (Excluding Tritium)

C.151   This code requires that the level of removable surface activity is essentially zero. Wiping is normally used in the fingerprinting process and as a confirmation that removable activity is indistinguishable from zero, given reasonable counting times etc. This is discussed fully in section 7.3.

C.152   In effect, during the fingerprinting process, at least part of the surface of interest has to be capable of reasonably accurate assessment by direct monitoring. This can then be wiped and the count rate from the wipe compared with the estimated removable surface activity generated by direct monitoring to produce a calibration for the wiping process.

C.153   Even where the bulk of any activity is expected to be firmly fixed to a surface, wiping can be useful. This is where it would be attractive to be able to estimate removable activity to a much lower level than can be achieved by direct monitoring assuming all activity is removable. (It is impossible to demonstrate that the level of removable activity on any contaminated surface is truly zero). If the surface is smooth, it may be possible, with care, to monitor up to an area of 1 m^2 by wipe, which can lead to maximum missable activities of less than 0.01 Bq cm^{-2} of both alpha and beta activity.

C.154   It is important to emphasise at this point that monitoring by wipe is a very uncertain process. The various aspects of this uncertainty will be discussed in each section.

Procedure:

C.155   The area to be wiped should be identified and gridded out. The material for the wipe should be selected. Generally, glass fibre based wipes are used as these are reasonably robust, have a good pick-up factor and leave the activity close to the surface of the wipe. However, depending on the chemistry of the expected contaminant, other materials such as thin polystyrene sheet have been used. Wipes can be used dry or moistened with either water or alcohol. The decision between wet and dry wiping depends on the chemistry and physical characteristics of the contaminant, on the condition of the surface being wiped and on the process used to count the activity on the wipes. Dry wiping generally has a lower pick-up factor but leaves activity close to the surface of the wipe where it is easier to count in conventional sample counters. Wipes also tend to be damaged more quickly when used wet and often should be dried before counting.

C.156   The wipe should be rubbed with uniform pressure over the area of interest. This is difficult to achieve consistently. Many users fold the wipe twice to give a quarter circle shape. This makes the wipe reasonably stiff which helps the application of a consistent pressure. It is then held in the fingers and wiped over the surface. There are two major uncertainties. One is the effective pressure on the wipe and the other is the fraction of the surface which is actually wiped. There have been holders used which impose a constant pressure which are useful for flat surfaces but that technique is impossible for complicated objects. Both these potential problems, pressure and fraction of the area wiped, can be minimised by training and supervision.

Counting:

C.157   The completed wipe is, essentially, just another potentially contaminated object for checking. For direct monitoring, the wipe should be unfolded carefully, flattened out and, if necessary, dried. Care should be taken not to knock activity off the wipe. The wipe can then be placed into a counting drawer. For alpha nuclides, these are usually large area silicon diode based but scintillation detectors can also be used. For beta counting, either a pancake GM detector is used or, increasingly, the measurement of beta activity can be made using the same silicon diode detector used for alpha assessment. For the relatively rare situations where the contaminant is a pure gamma emitter, counting will have to take place in a well shielded enclosure using a sodium iodide or hpGe detector. Even when the material is a beta emitter, such as ^{60}Co, there may be advantages to using the gamma emissions, as these are not affected by the grubbiness of the wipe. The counting time is selected to give an answer of sufficient statistical power, taking into account background count rate and the efficiency (as a source) of the wipe to demonstrate that the removable activity on the surface is statistically indistinguishable from zero, within the constraints adopted.

C.158   For many materials and conditions, it is often better to count the wipe by liquid scintillation. Unless the surface under test is perfectly clean, in terms of grease and grime, the wipe will become distinctly soiled. For short range emissions, this grime may effectively screen the bulk of the activity from a normal alpha or beta detector. Liquid scintillation can help overcome these problems. The activity of wipes placed in the scintillant will often float off, as will the grime. This means that the activity will be in intimate contact with the scintillant. The main problem with this approach is that the grime may adversely affect the scintillant cocktail (quenching), leading to less light generation per decay and may also produce chemi-luminescence, leading to false counts.

Calculation:

C.159   The aim of the process is to make an estimate of the fraction of loose surface activity on a defined surface area which may be missed. This is not trivial. Assessment of the activity on the wipe is difficult, with major uncertainties produced by the effects of attenuation by grime and of driving the activity into the surface. An easy way to get a reasonable correction factor is to count, by whatever preferred routine method, a number of wipes from a known contaminated area which is representative of the total area in question and then to bulk these wipes and analyse these radiochemically. This will yield a good measure of the count rate from the routine instrument per becquerel on the wipe.

C.160   The main use of conventional calibration sources is to demonstrate that the counting equipment is typical of type and that it is operating consistently. Using the apparent efficiency in counts s-1 Bq-1 to calculate the response to real contamination is only really valid where the condition of the wipe is unimportant. This is the case for direct counting of gamma counting and hard beta radiation. However it is not valid for alpha and soft beta activity assessed using a normal alpha or beta drawer unit.

C.161   The most effective approach is to wipe the whole area of interest. However, for large areas it is often satisfactory to wipe a consistent fraction of the area, provided any contaminant is likely to be relatively evenly distributed. The thoroughness and consistency of the area wiped is likely to be one of the major considerations in clearance monitoring. Training can be performed using a light coating of fine but visible powder on a trial surface. Consistency of performance is much more difficult where there is no visible track.

C.162   Pick-up factor is conventionally taken as 10%. This has stood the test of time and a variety of practical tests have yielded values between, generally, 10 and 30% for a variety of surfaces, wiping techniques and contaminants but ISO recommends a cautious value of 10%. Moist wipes can yield higher values.

C.163   This gives the following equation:

K = ((N –B) x R x 10)/(T x A xF)

where K = activity per unit area (Bq)

N = total count over time T

B = background over the same time, T

R = radiochemically derived activity (Bq) per unit count rate

T = counting time

A = area addressed

F = fraction of the area wiped

The factor of 10 corrects for the assumed 10% pick-up

C.164   The same equation can be used for liquid scintillation counting.

C.165   The uncertainties are extremely large. The aim has to be to produce a value which is conservative even assuming a relatively pessimistic assessment of the uncertainties. If the apparent activity is acceptable then we can have confidence that the real activity meets the criterion.

Appendix D   Statistical Tests and Assumptions

D.1   Default Value for Significance Level

D.1   This is a value judgement based upon guidance given by Defra and the Environment Agency in Section 3.63 of the Contaminated Land Report CLR 10. As noted in CLR 10, a balance must be struck between taking worst-case circumstances that may lead to implausible outcomes, and undue optimism that erodes protection of sensitive receptors. The application of a statistical test to data from a particular sentencing mass or area of material will only exempt the material if there is at least a 95% confidence level (i.e. 5% significance level) that the material is below the activity limit for clearance. In many instances, the sampled activity will fall well below the clearance level and the confidence level will be much higher than 95%.

D.2   The justification for choosing the 5% significance level is based on a reasonable worst case situation. This balances using Best Practical Means to minimise radioactive waste arisings with keeping exposure as low as reasonably practicable - the ALARP principle - and introduces an implied cost-benefit test. This level of significance is already in use as the default level for assessment of chronic risks to human health from exposure to chemicals in the ground.

D.3   It should also be remembered that conservative assumptions are built into the clearance process when setting clearance limits and these will be based on judgements about risk levels for other criteria than just the sampling process. Ultimately the total risk arising from the judgements made about each component of the analysis, when combined, should be very low.

D.4   A complementary reason for setting confidence at the proposed reasonable worst case level relates to the over-arching objectives for waste management set out in Chapter 4. These promote the principles of waste minimisation and the avoidance of unnecessary creation of radioactive waste. If the confidence level is set too high, a substantial amount of material will be sentenced as low level waste that should in practice be designated exempt. Furthermore, if sentencing regimes are made too onerous, sampling times and costs will escalate. In this case, decisions will be made to allocate materials which should be exempt into low level waste categories as a pragmatic alternative to spending time and money on better informed sentencing.

Table D.1. Examples of Everyday Materials and their Heterogeneity Class

Description	General Examples of Materials	Heterogeneity class	Specific Example of Materials
Surface contaminated items with impervious surfaces which may have been contaminated, but not activated or tritiated	Ceramic filter media Bench tops Glove box screens Wall/floor tiles Plant items	1 (symmetric)	PWR PC CRUD
		2 (skewed)	Uncontained process residue
High surface area to volume items which may have been contaminated, but not activated or tritiated	Clothing, paper, sheets of metal, polythene sheeting	1 (symmetric)	Single simple items
		2 (skewed)	Mixture of simple items
Solid items and materials which have a history of irradiation and activation occurs in the bulk of the solids	PWR Reactor plant structure	1 (symmetric)	Simple individual plant components
		2 (skewed)	Mixtures of plant components
Solid items and materials which have a history of exposure to tritium and tritiation has occurred in the bulk of the solids	Flooring, sewage bed sludge	1 (symmetric)	Tritiated alcohol
		2 (skewed)	GTLS workshops
Loose solids	Soils, sediments, sludges, vacuum dust, swarf	1 (symmetric)	Pile of soil / spoil
		2 (skewed)	Boiler house ash and clinker
Porous solids	Concrete, bricks, plaster	1 (symmetric)	A small concrete slab
		2 (skewed)	Pile of bricks
Impervious solids with accessible surfaces	Metal transport flask or ISO container, large section ducting	1 (symmetric)	A length of pipe
		2 (skewed)	A complex of connected pipe work
Impervious solids with inaccessible surfaces	Mechanical equipment such as an excavator or pump or pipe work	1 (symmetric)	Small simple items
		2 (skewed)	Mixture of small simple items

D.1.1 Approaches to unbiased sampling

D.5   Generally, sampling strategies fall into two basic approaches:

♦ judgmental sampling - typically used to efficiently confirm the presence and nature of contaminants based on prior knowledge or as part of the initial characterisation; and

♦ Probabilistic or systematic sampling - used to obtain representative data on a specified area (or volume) of homogeneous material without any form of bias.

D.6   Judgmental sampling introduces bias into the choice of material to sample, and if such sample data were used in statistical tests, then the results would automatically fail the basic assumption of unbiased data which underpins the use of the tests. Systematic sampling is therefore a necessary pre-requisite for the application of statistical tests given in this appendix.

D.7   Efficient systematic sampling designs may be stratified (i.e. each zone to be sampled should be divided into regular sub-zones).

D.8   Entirely random sampling patterns can be perceived as being problematic, as they can result in very uneven sampling densities, which means that some parts of the material may receive a number of sampling points and others none at all. Whilst these methods are statistically valid, it is possible that relatively large areas of contamination could be missed altogether, although this is unlikely in real life. For this reason, random sampling patterns are not recommended.

D.9   However, whatever sampling pattern is finally selected, it is important to use an unbiased (random) starting point located anywhere within the area. Figure D.1 gives an indication of the different sampling patterns possible.

D.10   These patterns should only be applied to homogeneous areas, zoning should be used on inhomogeneous areas, and the patterns applied to the homogeneous zones.

Figure D.1.   Different possible sampling patterns
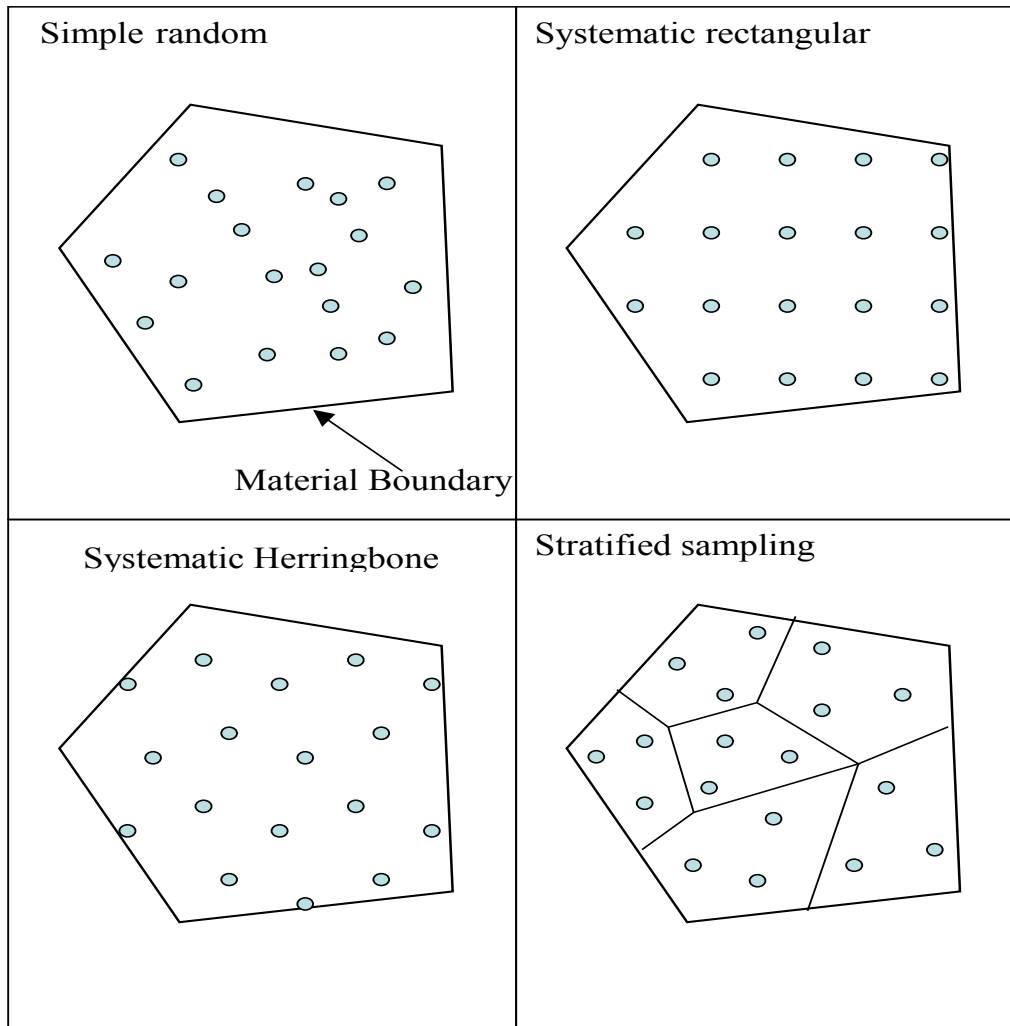
D.1.2 Post plots

D.11   Figure D.2 shows the location of the samples in space and the values observed at each location. It allows the trends in the data to be observed and if maps or other spatial data are overlaid on the post plot, possible associations with features in the material can be identified. As well as showing the location of samples it can indicate the magnitude of the sample results: as shown in the figure for a fictional facility. A random start herringbone grid has been employed.

Figure D.2.   Example post plot
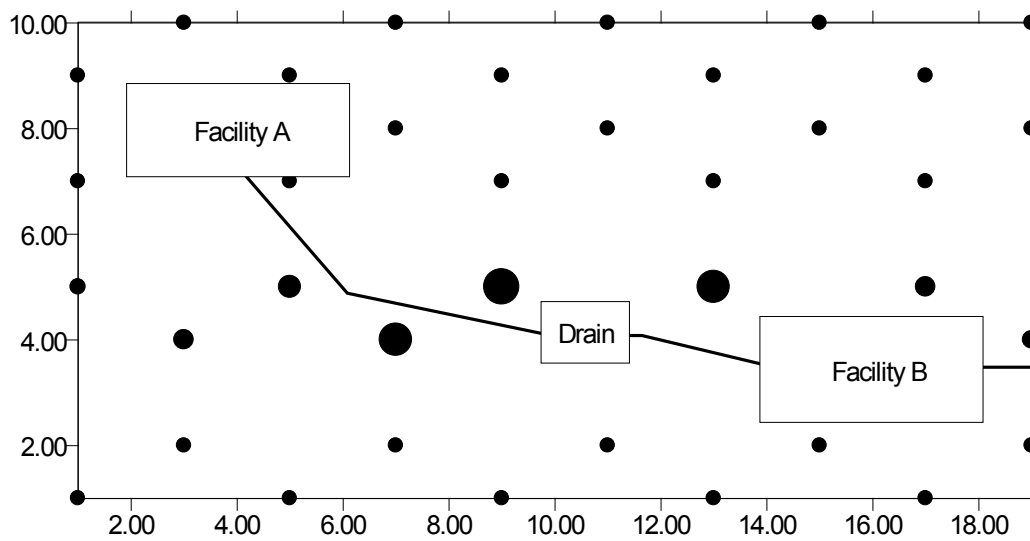
D.1.3 Contour plots

D.12   Contouring can reinforce the visualisation of spatial trends in the data as illustrated in Figure D.3. Care should be taken if automated contouring packages* are used to ensure that the contouring method is not introducing undesirable artefacts – spurious trends, for example.

Figure D.3.   Example contour graph

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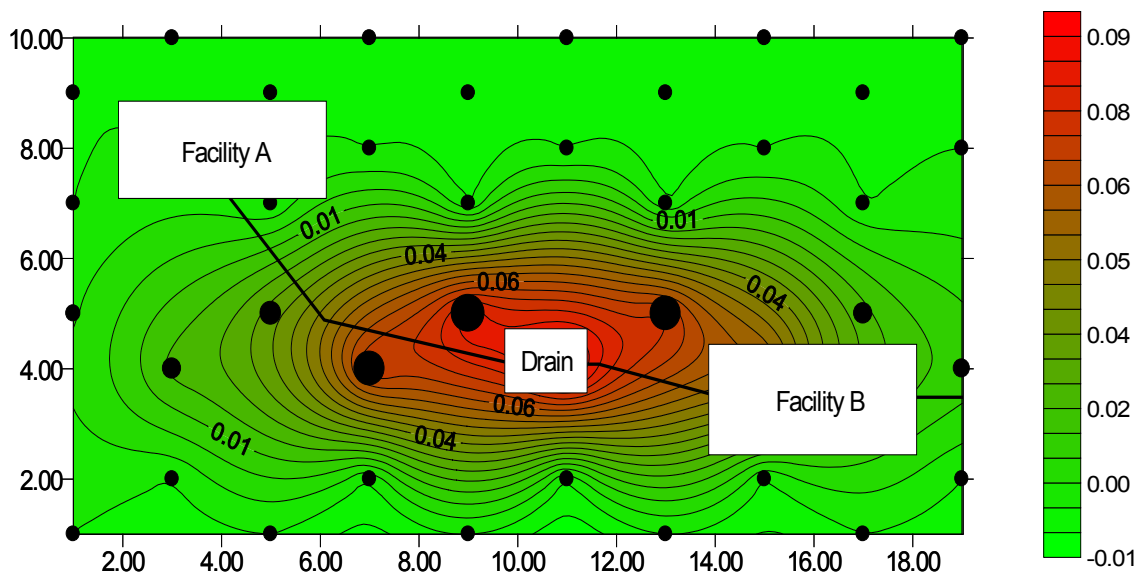
*   Interpolation of values between data points using software such as Surfer (www.golden.com) or a geographical information package such as Arc View (www.esri.com) or MapInfo (www.mapinfo.com) or free software (http://freegis.org) can be used to produce estimated contaminant contours.

D.1.4 Sample size calculation formulae

D.13   The sample size calculation formulae is:

$$N = (t_{\alpha,n-1} + t_{\beta,n-1})^2 \left(\frac{s}{\delta}\right)^2$$

Where:
α - False rejection (type I) error rate (1-confidence level)
β - False acceptance (type II) error rate (1-power level)
t_{α} - value of the Student's t-distribution at probability level* α

t_{β} - value of the Student's t-distribution at probability level[†] β

s – estimated standard deviation†
n – size of sample used to estimate s
δ - the size of difference you want to be able to detect in your sampling

D.14   The size of difference is the precision required for the sampling. For example, take an area of interest where the true average alpha value is 0.8 Bq g^{-1}. The area can only be sampled to estimate this alpha value as the whole area cannot be sampled. How far from 0.8Bq g^{-1} could the sample estimate deviate and still provide a useful estimate?   If, for a true average value of 0.8 an acceptable estimate would be between 0.7 and 0.9 then the size of difference (precision) would be 0.1. In reality the true alpha value is always unknown; however the size of difference or precision required of the estimate has to be chosen to enable the appropriate sample size to be calculated.

D.15   The size of difference (or precision) should reflect the degree of being non-radioactive that it would be wasteful to sentence as radioactive. This allows the cost of sampling to be weighed up against the cost of wrongful sentencing.

D.16   Where it is expected that a transformation is likely to be needed, the sample size calculations should use the standard deviation of the transformed prior/preliminary data, and a transformed difference.

D.17   For fixed sample sizes this same relationship can be used in any statistical software to estimate what level of type 2 error (β) to expect from the sample, informing the level of risk being taken. In statistical software, what is calculated is the power where power = 1 - β.

D.18   For example, if due to time and money constraints, only 10 samples could be taken it would be possible to use statistical software to work out the power, and hence the probability of a type II error by making some assumptions about what would be suitable values for the parameters defined in the sample size calculation formula.

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*   Can be calculated in excel using the TINV function – note that to use this function for one sided tests the alpha components of the formula needs to be doubled. So for a one sided test with 95% confidence, 70% power, where a sample of 100 had been used to estimate the standard deviation the excel functions would be TINV((1-0.95)*2), 99) and TINV((1-0.7),99)

†   If available this can be estimated from previous similar data. There is no set limit on the number of samples needed to estimate the standard deviation. However, sample size estimate will only be as good as the assumptions put into the calculation. Therefore, if you have a lot of data with which to estimate the standard deviation, you will be more sure about your sample size estimate. If it is based on a small number of data its worth calculating the sample size for a range of standard deviation to see how sensitive the overall calculation is to your estimate of sigma

So, if using previous data it was possible to estimate the standard deviation of any gathered data would be about 0.15; a reasonable size of difference from the limit that any sample should be able to detect is ± 0.1 and the significance level is 5% then software would give the output shown in Table D.2.

Table D.2. Calculated Power for a fixed sample size

t-test	(Sig level= 0.05 Sigma = 0.15)	
Difference	Sample Size	Power
0.1	10	0.6185

D.19   It can be seen from Table D.2 that under these conditions, a sample size of 10 would give a power of 0.6185 and hence the probability of a Type II error would be 1-0.6185=0.3815.

D.20   Figure D.4 shows the relationship between sample size and power for differing standard deviation assumptions in the case of wanting to be able to detect a difference of at least 0.1 and a 5% significance level.

Figure D.4.   Plot of sample size versus power for different standard deviation assumptions

5% significance; 0.1 size of difference
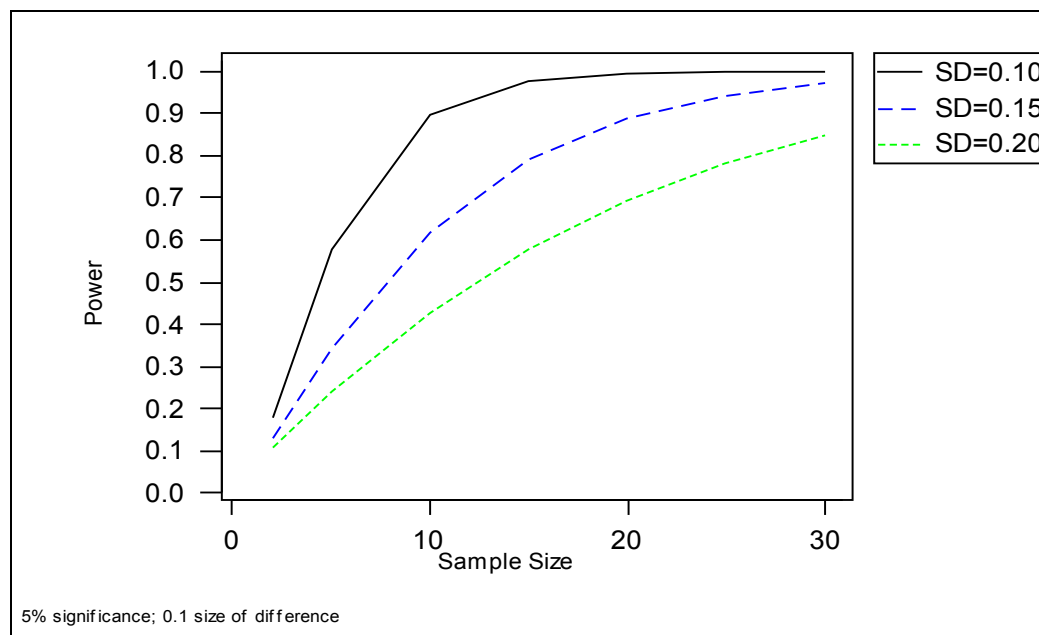
D.2 Wilcoxon Signed Ranks test

D.21   A staged approach is adopted.
Stage 1: Assign values to any observations below the detection limit. If this is not possible, assign a value of 'detection limit/2' to these observations.

Stage 2: Subtract each sample value Z_i from Z_T to obtain the set of sample deviations d_i. If any of the deviations are zero they should be deleted from the list and the sample size N reduced accordingly.

Stage 3: Order the absolute deviations $|d_i|$ from smallest to largest. Rank the list. Rank 1 is assigned to the smallest value, then rank 2 to the second smallest value, etc.

If two or more of the absolute deviations have an equal value, assign the average of the ranks which would have been assigned to them.

Stage 4: Construct the signed rank by assigning the sign of each deviation to its rank in the list. The sign is positive if the deviation d_i is positive ($d_i > 0$).

Stage 5: Calculate the sum of the ranks with a positive sign, w.

Stage 6: Test the hypothesis by comparing w with the critical value w_{crit}

D.22   Calculate w_{crit} using the equation below.

$$w_{crit} = \frac{n(n+1)}{4} + z_\alpha \sqrt{n(n+1)(2n+1)/24}$$

where z_α = the α percentile of the standard normal distribution)

D.23   If the number of samples is less than or equal to 20 then:

If $w > n(n+1)/2 - w_{crit}$, the material is exempt (the null hypothesis may be rejected).

Otherwise the material is not exempt (there is not enough evidence to reject the null hypothesis)

D.24   Else if the number of samples is greater than 20 then:

If $w > w(crit)$ reject the null hypothesis (the material is exempt).

Otherwise the material is not exempt (i.e. there is not enough evidence to reject the null hypothesis)

D.3   Students t test for H_0 $\mu \geq Z_T$; H_1 $\mu < Z_T$

Stage 1:   Calculate the mean of the sample $\overline{Z} = \frac{1}{n}\sum_{i=1}^{n} Z_i$

Stage 2:   Calculate the standard deviation of the sample $s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(Z_i - \overline{Z})^2}$

Stage 3:   Obtain the critical value, t_{crit}, from Table D.3 for the chosen significance level 100(1-α)% and the number of degrees of freedom (n-1).

Stage 4:   Compute the test statistic, t, using

$$t = \frac{(Z_T - \overline{Z})}{(s/\sqrt{n})}$$

Stage 5:   If $t > t_{crit}$ then the material is exempt (reject the null hypothesis). Otherwise the material is radioactive (accept the null hypothesis).

D.25   Report the values of $\overline{Z}$, Z_T, n, t_{crit}, t and the result.

D.26   The stage 5 rejection criterion is only suitable for hypotheses that follow the same format as the one stated above. Any hypothesis which examines whether the mean value is less than a limit or aims to investigate whether the mean is different (could be either greater or less than) a limit would require a different rejection criterion.

Table D.3. Critical value for t test

Degrees of Freedom	1 - α								
	.70	.75	.80	.85	.90	.95	.975	.99	.995
1	0.727	1.000	1.376	1.963	3.078	6.314	12.706	31.821	63.657
2	0.617	0.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925
3	0.584	0.765	0.978	1.250	1.638	2.353	3.182	4.541	5.841
4	0.569	0.741	0.941	1.190	1.533	2.132	2.776	3.747	4.604
5	0.559	0.727	0.920	1.156	1.476	2.015	2.571	3.365	4.032
6	0.553	0.718	0.906	1.134	1.440	1.943	2.447	3.143	3.707
7	0.549	0.711	0.896	1.119	1.415	1.895	2.365	2.998	3.499
8	0.546	0.706	0.889	1.108	1.397	1.860	2.306	2.896	3.355
9	0.543	0.703	0.883	1.100	1.383	1.833	2.262	2.821	3.250
10	0.542	0.700	0.879	1.093	1.372	1.812	2.228	2.764	3.169
11	0.540	0.697	0.876	1.088	1.363	1.796	2.201	2.718	3.106
12	0.539	0.695	0.873	1.083	1.356	1.782	2.179	2.681	3.055
13	0.538	0.694	0.870	1.079	1.350	1.771	2.160	2.650	3.012
14	0.537	0.692	0.868	1.076	1.345	1.761	2.145	2.624	2.977
15	0.536	0.691	0.866	1.074	1.34	1.753	2.131	2.602	2.947
16	0.535	0.690	0.865	1.071	1.337	1.746	2.120	2.583	2.921
17	0.534	0.689	0.863	1.069	1.333	1.740	2.110	2.567	2.898
18	0.534	0.688	0.862	1.067	1.330	1.734	2.101	2.552	2.878
19	0.533	0.6880	0.861	1.066	1.328	1.729	2.093	2.539	2.861
20	0.533	.687	0.860	1.064	1.325	1.725	2.086	2.528	2.845
21	0.532	0.686	0.859	1.063	1.323	1.721	2.080	2.518	2.831
22	0.532	0.686	0.858	1.061	1.321	1.717	2.074	2.508	2.819
23	0.532	0.685	0.858	1.060	1.319	1.714	2.069	2.500	2.807
24	0.531	0.685	0.857	1.059	1.318	1.711	2.064	2.492	2.797
25	0.531	0.684	0.856	1.058	1.316	1.708	2.060	2.485	2.787
26	0.531	0.684	0.856	1.058	1.315	1.706	2.056	2.479	2.779
27	0.531	0.684	0.855	1.057	1.314	1.703	2.052	2.473	2.771
28	0.530	0.683	0.855	1.056	1.313	1.701	2.048	2.467	2.763
29	0.530	0.683	0.854	1.055	1.311	1.699	2.045	2.462	2.756
30	0.530	0.683	0.854	1.055	1.310	1.697	2.042	2.457	2.750
40	0.529	0.681	0.851	1.050	1.303	1.684	2.021	2.423	2.704
60	0.527	0.679	0.848	1.046	1.296	1.671	2.000	2.390	2.660
120	0.526	0.677	0.845	1.041	1.289	1.658	1.980	2.358	2.617
	0.524	0.674	0.842	1.036	1.282	1.645	1.960	2.326	2.576

Note: The last row of the table (degrees of freedom) gives the critical values for a standard normal distribution (z), e.g., $t_{,0.95}$ = $z_{0.95}$ = 1.645.

Appendix E   Derivation of an Out of Scope Activity Concentration Limit

E.1   Background

E.1   Calcium-41 is a weak electron capture X-ray emitter present in the DRAGON bioshield which is now being considered for off-site release. Table 2 of Schedule 23 of EPR2011 defines the activity concentrations that are 'out of scope' of the regulations. This table does not give a value for ^{41}Ca and the default value for radionuclides for which no value is specified in Table 2 is 0.01 Bq g^{-1}. However, the regulations do permit the derivation of radionuclide specific activity concentration limits based on the principles set out in RP122 Part 1 [1].

E.2   Laboratories generally struggle to measure activity at 0.01 Bq g^{-1} and, therefore, Research Sites Restoration Ltd (RSRL) commissioned a study to determine a more appropriate 'out of scope' level for ^{41}Ca. The regulations allow for users to derive radionuclide specific values, subject to approval by the relevant regulatory authority.

E.3   That study is summarised here. The general approach adopted provides a worked example for the derivation of specific activity concentrations for other radionuclides not included in Table 2 of Schedule 23 of EPR2011, to identify out of scope materials and wastes, subject to approval of the derived value by the relevant regulator.

E.2   Methodology

E.4   The approach used was to adopt the method set out in RP122 Part 1 using appropriate radionuclide specific parameter values for ^{41}Ca (e.g. dose per unit intake) from existing databases.

E.2.1 RP122 methodology

E.5   The methodology described in RP122 Part 1 calculates the dose per unit concentration in solid material for four main exposure scenarios: inhalation, ingestion, external exposure and skin exposure. For each main scenario, two or three sub-scenarios were considered. The scenario giving rise to the highest dose was then selected and compared with a dose criterion of 10 μSv y^{-1} to obtain the corresponding activity concentration in Bq g^{-1}. This was then rounded to the nearest power of 10 using the following rounding rule:

$$3 \cdot 10^n < x < 2.9 \cdot 10^{n+1} \rightarrow 10^{n+1}$$

Where x is the activity concentration (Bq g^{-1}).

E.6   The rounded values were then compared with the clearance levels that had already been derived for metals [2] and building materials [3] and the lowest value was selected. These were then termed the 'general clearance levels' and are listed in Table 1 in RP122 Part 1 (Table 3-1 in RP122 Part 1 contains the unrounded values). These general clearance levels are the values that have been incorporated into Table 2 of Schedule 23 of EPR2011 as 'Out of Scope' levels.

E.2.2 Summary of exposure scenarios

E.7 Two inhalation scenarios were considered in RP122 Part 1. The descriptions of the scenarios, the formula and parameter values are given in the following extracts from RP122 Part 1.

Inhalation of contaminated dust can occur in many exposure situations. Therefore, two conservative enveloping scenarios are chosen which represent exposure at a workplace and exposure of the general population respectively. An infant (age group 0-1 a) is chosen as the enveloping age group in the latter case[3]. Doses from inhalation are calculated according to (1):

$$H_{inh,C} = h_{inh} \cdot t_e \cdot f_d \cdot f_c \cdot C_{dust} \cdot V \cdot e^{-\lambda t_1} \frac{1 - e^{-\lambda \cdot t_2}}{\lambda \cdot t_2} \tag{1}$$

Where

$H_{inh,C}$	[(µSv/a)/(Bq/g)] annual individual effective dose from inhalation per unit activity concentration in the cleared material,
h_{inh}	[µSv/Bq] dose coefficient for inhalation (cf. Section 2.3.),
t_e	[h/a] exposure time,
f_d	[-] dilution factor,
f_c	[-] concentration factor for the activity in the inhalable dust fraction,
C_{dust}	[g/m³] effective dust concentration in the air,
V	[m³/h] breathing rate,
λ	[1/a] radionuclide dependant decay constant,
t_1	[a] decay time before start of scenario,
t_2	[a] decay time during scenario.

- Scenario INH-A: Inhalation of dust at a workplace during the whole working year (1800 h/a). The dust is assumed to originate solely from the contaminated material (e.g. resuspension of dust from building rubble, waste or other material into the air), i.e. no dilution, and to be present with a concentration of 1 mg/m³ in the air. The activity concentration in the dust itself is assumed to be equal to the activity concentration in the cleared material, i.e. no concentration processes are taken into account. The breathing rate is set to 1.2 m³/h accounting for moderate activity. Dose coefficients are taken from Table C of [CEU 96] for 5 µm AMAD (Activity Median Aerodynamic Diameter). No decay before and during the scenario is assumed because the dust could always originate from freshly cleared material.

- Scenario INH-B: Inhalation of dust during a whole year (8760 h/a) by an infant. 10% of the inhaled dust is assumed to originate from contaminated material (e.g. dust near a landfill site), and to be present with a concentration of 0.1 mg/m³ in the air. The breathing rate is set to 0.24 m³/h. Dose coefficients are taken from Table B of [CEU 96] for the default lung retention class and the age group 0-1 a. No decay before and during the scenario is assumed because the dust can always originate from freshly cleared material.

Reproduced from Section 2.4.1 of RP122, Part 1 [1].

Table E.1. Scenario parameters for inhalation scenarios

Parameter	Unit	Scenario INH-A	Scenario INH-B
Exposure time t_e	h/a	1800	8760
Dilution factor f_d	[-]	1	0.1
Concentration factor in dust f_c	[-]	1	1
Breathing rate V	m³/h	1.2	0.24
Dust concentr. in air C_{dust}	g/m³	1.00E-03	1.00E-04
Decay time before scenario t_1	d	0	0
Decay time during scenario t_2	d	0	0
Dose coefficient h_{inh}	µSv/Bq	5 µm, worker; cf. section 2.3.	0-1 a, default, cf. section 2.3.

Reproduced from Table 2.2 of RP122, Part 1 [1].

E.8   Two ingestion scenarios were considered in RP122 Part 1. The descriptions of the scenarios, the formula and parameter values are given in the following extracts from RP122 Part 1.

Inadvertent ingestion of contaminated material can occur in many exposure situations. As for inhalation, two scenarios are considered which cover workplaces and the general public. The dose from ingestion is calculated according to (2).

$$H_{ing,C} = h_{ing} \cdot q \cdot f_d \cdot f_c \cdot e^{-\lambda t_1} \frac{1 - e^{-\lambda \cdot t_2}}{\lambda \cdot t_2} \tag{2}$$

Where

$H_{ing,C}$ [(µSv/a)/(Bq/g)] annual individual effective dose from ingestion per unit activity concentration in the cleared material,

h_{ing} [µSv/Bq] dose coefficient for ingestion (cf. Section 2.3.),

q   [g/a] ingested quantity per year,

f_d [-] dilution factor,

f_c [-] concentration factor for the activity in the ingested material,

λ [1/a] radionuclide dependant decay constant,

t_1 [a] decay time before start of scenario,

t_2 [a] decay time during scenario.

• Scenario ING-A: A worker working in an environment where it is possible to ingest material (e.g. hand-to-mouth-pathway). The ingested quantity is assumed to be 20 g/a with no dilution or concentration processes. As the worker might always ingest fresh material, no

  decay before or during the scenario is assumed. The ingestion dose coefficients are taken from Table C of [CEU 96].
• Scenario ING-B: A small child (age 1 to 2 a) playing on soil or ground which consists of undiluted material having been cleared from a nuclear site. The ingested quantity is assumed to be 100 g/a with no dilution or concentration processes. As the material will not be exchanged, a decay of 1 d before the scenario and a whole year during the scenario is assumed. The ingestion dose coefficients are taken from Table A of [CEU 96] for the age group 1-2 a.

Reproduced from Section 2.4.2 of RP122, Part 1 [1].

Table E.2. Scenario parameters for ingestion scenarios

Parameter	Unit	Scenario ING-A	Scenario ING-B
Annually ingested quantity q	g/a	20	100
Dilution factor f_d	[-]	1	1
Concentration factor f_c	[-]	1	1
Decay time before scenario t_1	d	0	1
Decay time during scenario t_2	d	0	365
Dose coefficient h_{ing}	µSv/Bq	worker; cf. section 2.3.	1-2 a, cf. section 2.3.

Reproduced from Table 2.3 of RP122, Part 1 [1].

E.9   Three external irradiation scenarios were considered in RP122 Part 1.   The descriptions of the scenarios, the formula and parameter values are given in the following extracts from RP122 Part 1.

Exposure situations in which external irradiation is relevant are most likely encountered on a landfill where cleared waste is disposed of (landfill worker), during transport and while staying in a building that is constructed using cleared building rubble as aggregate for the new concrete. Other conceivable exposure situations of radiological significance will be covered if sufficiently conservative parameters are chosen. The dose from external irradiation is calculated according to (3):

$$H_{ext,C} = h_{ext} \cdot t_e \cdot f_d \cdot e^{-\lambda t_1} \frac{1 - e^{-\lambda \cdot t_2}}{\lambda \cdot t_2} \qquad (3)$$

Where

$H_{ext,C}$ [(µSv/a)/(Bq/g)] annual individual effective dose from external irradiation per unit activity concentration in the cleared material,

h_{ext} [(µSv/h)/(Bq/g)] effective dose rate per unit activity concentration in the cleared material, depending on geometry, distance, shielding etc.

f_d [-] dilution factor,

t_e [h/a] exposure time,

λ [1/a] radionuclide dependent decay constant,

t_1 [a] decay time before start of scenario,

t_2 [a] decay time during scenario.

- Scenario EXT-A: A landfill worker who is working full-time (1800 h/a) on the waste. It is assumed that the waste contains 10% contaminated material. A decay of 1 day before the scenario (transport time between site of clearance and landfill) is assumed, however, no decay time during the scenario because for a landfill, the waste the worker is dealing with will contain always fresh material. A homogeneously distributed activity in the waste for which conservatively a densitiy of 2 g/cm³ is assumed is taken as the exposure geometry. Doses are calculated for rotational exposure at 1m height above ground. This scenario might also describe other persons who work on a ground whose cover contains cleared material, e.g. a person at a gas station where the pavement is made using recycling concrete from nuclear facilities.

- Scenario EXT-B: A truck driver who transports cleared material (e.g. steel scrap) for 200 h/a. During transport, no mixing with uncontaminated material is assumed. A truck load of 5 · 2 · 1 m³ with a mean density of 2 g/m³ and a distance to the driver of 1 m from the small edge of load without additional shielding is taken as the exposure geometry. Doses are calculated for a posterior-anterior geometry. Because always fresh material is transported, no decay is assumed before and during the scenario. This scenario also describes situations in which a person is working near a large item, e.g. a large machine or cabinet which has been cleared for reuse.

- **Scenario EXT-C:** A person living 7000 h/a in a house for which cleared building rubble has been used in the construction. It is assumed that cleared material is used for 2% of the entire building. The exposure geometry is chosen as a room of 3 · 4 m² and 2.5 m height with floor, walls and ceiling of 20 cm thickness. Doses are calculated for the middle of the room at a height of 1 m. In order to account for windows, shielding by furniture etc., the contributions from the floor (counted twice to include the ceiling) and two walls (4 · 2.5 m²) are summed. Doses are calculated for a rotational geometry at 1 m height above ground. A decay of 100 d before the start of the scenario and of a whole year during the scenario is assumed.

Reproduced from Section 2.4.3 of RP122, Part 1 [1].

Table E.3. Scenario parameters for external irradiation scenarios

Parameter	Unit	Scenario EXT-A	Scenario EXT-B	Scenario EXT-C
Exposure time t_e	h/a	1800	200	7000
Dilution factor f_d	[-]	0.1	1	0.02
Decay time before scenario t_1	d	1	0	100
Decay time during scenario t_2	d	0	0	365
Geometry		1 m above ground, semi-infinite source	1 m from load 5x2x1m³, no shielding	floor, ceiling, 2 walls, 3x4 m², 20 cm wall thickness
Dose coefficient h_{ext}	μSv/h/(Bq/g)	depending on radionuclide and geometry, cf. Section 2.3., see table 5-2		

Reproduced from Table 2.4 of RP122, Part 1 [1].

E.10   Skin contamination is also considered in RP122 Part 1. The scenario description, the formula and parameter values are given in the following extracts from RP122 Part 1.

Skin contamination by dust containing radionuclides can only occur with some significance at workplaces in dusty environments. The effective individual dose from skin contamination is calculated according to (4).

$$H_{skin,C} = h_{skin} \cdot w_{skin} \cdot f_{skin} \cdot t_e \cdot L_{dust} \cdot f_d \cdot f_c \cdot \rho \cdot e^{-\lambda \cdot t_1} \frac{1 - e^{-\lambda \cdot t_2}}{\lambda \cdot t_2} \quad (4)$$

Where

$H_{skin,C}$ [(μSv/a)/(Bq/g)] annual effective individual dose from skin contamination with beta and gamma emitters per unit activity concentration in the cleared material,

h_{skin} [(μSv/h)/(Bq/cm²)] sum of skin dose coefficients for beta emitters (4 mg/cm² skin density) and for gamma emitters [KOC 87] per surface specific unit activity,

w_{skin} [-] skin weighting factor according to ICRP 60,

f_{skin} [-] fraction of body surface which is contaminated,

t_e [h/a] exposure time (time during which the skin is contaminated),

L_{dust} [cm] layer thickness of dust loading on the skin,

f_d [-] dilution factor,

f_c [-] concentration factor for the activity in the ingested material,

ρ [g/cm³] density of surface layer

λ [1/a] radionuclide dependant decay constant,

t_1 [a] decay time before start of scenario,

t_2 [a] decay time during scenario.

> • Scenario SKIN: a worker in a dusty environment. It is assumed that during a whole working year (1800 h/a) both forearms and hands (10% of the total body surface)[4] are covered with a dust layer of 100 μm (0.01 cm) thickness. The dust is assumed to have the same activity concentration as the cleared material. As the material on the skin might always be fresh, no decay before or during the scenario is assumed. The density of the dust on the skin is set to 1.5 g/cm³. In order to calculate effective doses, the dose coefficients from [KOC 87] have to be multiplied with a skin weighting factor of 0.01.

Reproduced from Section 2.4.4 of RP122, Part 1 [1].

Table E.4. Scenario parameters for skin contamination scenario

Parameter	Unit	Scenario SKIN
Exposure time t_e	h/a	1800
Layer thickness L_{dust}	cm	0.01
Dust density ρ	g/cm³	1.5
Dilution factor f_d	[-]	1
Concentration factor f_c	[-]	1
Skin weighting factor w_{skin}	[-]	0.01
Fraction of body surface f_{skin}	[-]	0.1 (eq. ca. 2000 cm²)
Decay time before scenario t_1	d	0
Decay time during scenario t_2	d	0
Dose coefficient h_{skin}	(μSv/h)/(Bq/cm²)	depending on radionuclide, cf. section 2.3., see table 5-2

Reproduced from Table 2.5 of RP122, Part 1 [1].

E.2.3 Spreadsheet implementation

E.11   The formulae and data described in RP122 Part 1 and listed in Section 2 were implemented in an Excel spreadsheet written specifically for this project. The spreadsheet was then used to calculate the general clearance levels for sixteen radionuclides in order to demonstrate that it was able to reproduce the RP122 Part 1 methodology correctly. The sixteen radionuclides covered a range of half-lives and radioactive decay modes.

E.3   Testing the spreadsheet

E.3.1 RP122 results

E.12   The unrounded dose per unit activity concentration results are given in Table 3-1 of RP122 Part 1, for the eight scenarios. The values for the sixteen selected radionuclides are reproduced in Table E.5, which is composed of extracts from Table 3-1 of RP122 Part 1. These are the same as the values given in Table 2 of Schedule 23 of EPR2011, the 'out of scope' levels.

Table E.5. Results of dose calculations for all nuclides and scenarios as listed in RP122 Part 1

| Nuclide | T$_{1/2}$ (a) | Dose µSv y^{-1} per Bq g^{-1} | | | | | | | | | Limiting scenario |
| | | External Irradiation | | | Inhalation | | Ingestion | | Skin | Max | |
		EXT-A	EXT-B	EXT-C	INH-A	INH-B	ING-A	ING-B			
H-3	1.2E+01	0.0E+00	0.0E+00	0.0E+00	8.9E-05	7.1E-06	8.4E-04	1.2E-02	0.0E+00	1.2E-02	ING-B
Be-7	1.5E-01	1.4E+00	3.8E-01	1.3E-01	9.3E-05	5.3E-06	5.6E-04	2.8E-03	7.4E-05	1.4E+00	EXT-A
C-14	5.7E+03	0.0E+00	0.0E+00	0.0E+00	1.3E-03	1.7E-04	1.2E-02	1.6E-01	2.4E-02	1.6E-01	ING-B
Ca-45	4.5E-01	0.0E+00	0.0E+00	0.0E+00	5.0E-03	2.5E-04	1.5E-02	2.5E-01	4.3E-02	2.5E-01	ING-B
Ca-47	1.2E-02	3.1E+01	9.6E+00	1.1E-07	5.2E-03	2.5E-04	3.7E-02	1.6E-02	1.3E-01	3.1E+01	EXT-A
Sc-47	9.2E-03	1.9E+00	2.3E-01	0.0E+00	1.6E-03	8.4E-05	1.1E-02	4.2E-03	4.3E-02	1.9E+00	EXT-A
Fe-55	2.7E+00	0.0E+00	0.0E+00	0.0E+00	7.1E-04	4.0E-05	6.6E-03	2.1E-01	4.3E-04	2.1E-01	ING-B
Co-60	5.3E+00	8.4E+01	2.3E+01	1.0E+02	1.5E-02	8.8E-04	6.8E-02	2.5E+00	5.3E-02	1.0E+02	EXT-C
Tc-99	2.1E+05	7.8E-06	4.3E-08	1.2E-05	6.9E-03	3.6E-04	1.6E-02	4.8E-01	4.3E-02	4.8E-01	ING-B
I-131	2.2E-02	9.8E+00	2.6E+00	9.1E-05	2.4E-02	1.5E-03	4.8E-01	5.2E-01	6.5E-02	9.8E+00	EXT-A
Cs-134	2.1E+00	4.8E+01	1.3E+01	5.4E+01	2.1E-02	2.3E-04	3.8E-01	1.4E+00	5.2E-02	5.4E+01	EXT-C
Cs-137	3.0E+01	1.8E+01	4.9E+00	2.6E+01	1.4E-02	1.9E-04	2.6E-01	1.2E+00	6.9E-02	2.6E+01	EXT-C
Pb-210	2.2E+01	7.3E-03	7.0E-05	1.4E-02	6.9E+00	4.0E-01	1.8E+01	1.2E+03	7.1E-02	1.2E+03	ING-B
Bi-210	1.4E-02	7.8E-06	2.4E-06	0.0E+00	2.8E-01	1.8E-02	1.8E-01	5.1E-01	7.1E-02	5.1E-01	ING-B
Po-210	3.8E-01	2.8E-04	7.6E-05	1.1E-04	4.8E+00	3.2E-01	4.8E+00	4.0E-02	1.3E-08	4.8E+00	ING-B
Pu-239	2.4E+04	9.6E-04	3.7E-05	1.5E-03	6.9E+01	1.7E+00	5.0E+00	4.2E+01	3.9E-05	6.9E+01	INH-A

Extracted from Table 3.1 of RP122, Part 1 [1].

E.3.2 Results obtained using the spreadsheet

E.13   The results that were obtained using the spreadsheet for the sixteen selected radionuclides are given in Table E.6. A comparison between these results and the results in RP122 Part 1 was undertaken and the agreement was found to be very good in all cases.

Table E.6. Dose per unit activity concentration for the different scenarios calculated using the spreadsheet

| Nuclide | Half life (y) | Dose per unit activity concentration (µSv y^{-1} per Bq g^{-1}) | | | | | | | | | Limiting scenario |
| | | External Irradiation | | | Inhalation | | Ingestion | | SKIN | Maximum value | |
		EXT-A	EXT-B	EXT-C	INH-A	INH-B	ING-A	ING-B			
H-3	1.20E+01	0.00E+00	0.00E+00	0.00E+00	8.86E-05	7.15E-06	8.40E-04	1.17E-02	0.00E+00	1.17E-02	ING-B
Be-7	1.50E-01	1.44E+00	3.80E-01	1.36E-01	9.29E-05	5.26E-06	5.60E-04	2.75E-03	7.39E-05	1.44E+00	EXT-A
C-14	5.70E+03	0.00E+00	0.00E+00	0.00E+00	1.25E-03	1.74E-04	1.16E-02	1.60E-01	2.43E-02	1.60E-01	ING-B
Ca-45	4.50E-01	0.00E+00	0.00E+00	0.00E+00	4.97E-03	2.52E-04	1.52E-02	2.49E-01	4.31E-02	2.49E-01	ING-B
Ca-47	1.20E-02	3.07E+01	9.60E+00	1.15E-07	5.18E-03	2.52E-04	3.60E-02	1.63E-02	1.29E-01	3.07E+01	EXT-A
Sc-47	9.20E-03	1.90E+00	2.40E-01	5.32E-11	1.58E-03	8.41E-05	1.08E-02	4.21E-03	4.31E-02	1.90E+00	EXT-A
Fe-55	2.70E+00	0.00E+00	0.00E+00	0.00E+00	7.13E-04	3.99E-05	6.60E-03	2.12E-01	4.31E-04	2.12E-01	ING-B
Co-60	5.30E+00	8.46E+01	2.20E+01	1.00E+02	1.53E-02	8.83E-04	6.80E-02	2.53E+00	5.24E-02	1.00E+02	EXT-C
Tc-99	2.10E+05	7.74E-06	4.20E-08	1.20E-05	6.91E-03	3.57E-04	1.56E-02	4.80E-01	4.31E-02	4.80E-01	ING-B
I-131	2.20E-02	9.74E+00	2.60E+00	9.57E-05	2.38E-02	1.51E-03	4.40E-01	5.24E-01	6.47E-02	9.74E+00	EXT-A
Cs-134	2.10E+00	4.86E+01	1.30E+01	5.45E+01	2.07E-02	2.31E-04	3.80E-01	1.36E+00	5.24E-02	5.45E+01	EXT-C
Cs-137	3.00E+01	1.80E+01	4.80E+00	2.61E+01	1.45E-02	1.85E-04	2.60E-01	1.19E+00	6.78E-02	2.61E+01	EXT-C
Pb-210	2.20E+01	7.38E-03	7.00E-05	1.37E-02	6.91E+00	3.99E-01	1.80E+01	1.18E+03	7.08E-02	1.18E+03	ING-B
Bi-210	1.40E-02	7.86E-06	2.40E-06	3.34E-13	2.81E-01	1.83E-02	1.80E-01	5.12E-01	7.08E-02	5.12E-01	ING-B
Po-210	3.80E-01	2.87E-04	7.60E-05	1.13E-04	4.75E+00	3.15E-01	4.80E+00	4.03E+02	1.29E-08	4.03E+02	ING-B
Pu-239	2.40E+04	9.54E-04	3.60E-05	1.54E-03	6.91E+01	1.68E+00	5.00E+00	4.20E+01	4.00E-05	6.91E+01	INH-A

E.4   Derivation of 'out of scope' level for ^{41}Ca

E.14   The 'out of scope' level for ^{41}Ca was calculated by obtaining the required radionuclide data for ^{41}Ca and then applying the RP122 Part 1 methodology as implemented in the spreadsheet.

E.4.1 Calcium-41 data

E.15   Calcium-41 decays by electron capture to ^{41}K, which is stable. It emits a spectrum of low energy X rays*, and the highest probability emission is an X-ray with an energy of 3.3 keV and an intensity of about 12%, see Table E.7.

Table E.7. X-ray emissions from ^{41}Ca

E (keV)	I (%)
0.296	0.013
0.359	0.0036
0.359	0.0058
3.230	5.8E-07
3.311	3.9
3.314	7.8
3.590	0.37
3.590	0.72

E.16   The radionuclide specific data for ^{41}Ca obtained from the same data sources as that used in RP122 Part 1, where possible. However, there are no values given for the dose rate from skin contamination by ^{41}Ca in the data sources used in RP122 Part 1, nor in other available publications consulted. Iron-55 also decays by electron capture and it emits a spectrum of X-rays ranging from 0.6 to 6.5 keV with the highest probability emissions at 5.9 keV; this equates to an X-ray energy of 5.9 keV with an intensity of about 25% [4]. Hence, the dose rates from skin contamination for ^{55}Fe can be used to provide an overestimate of the dose rate from ^{41}Ca since ^{41}Ca emits X-rays with lower energies and at a lower intensity. The values and data sources used for the ^{41}Ca specific data are given in Table E.8.

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*   http://ie.lbl.gov/toi/nuclide.asp?iZA=200041

Table E.8. Radionuclide specific data for Ca-41

Scenario	Parameter	Unit	Value	Notes
All	Half-life	y	1.40E+05	ICRP68 [5],ICRP72 [5], IAEA SS115 [6], FG12 [7]
INH-A	Dose per unit inhalation: adult	Sv Bq^{-1}	1.9E-10	ICRP68 [5], class M
INH-B	Dose per unit inhalation: infant	Sv Bq^{-1}	4.2E-10	ICRP72 [5], class M
ING-A	Dose per unit ingestion: adult	Sv Bq^{-1}	2.9E-10	ICRP68 [5]
ING-B	Dose per unit ingestion: 1 yr child	Sv Bq^{-1}	5.2E-10	ICRP72 [5]
EXT-A	Dose rate per activity concentration	µSv h^{-1} per Bq g^{-1}	0.0E+00	FG12 [7], Tables 3.3 and 3.7
EXT-B	Dose rate per activity concentration	µSv h^{-1} per Bq g^{-1}	0.0E+00	FG12 [7], Tables 3.3 and 3.7
EXT-C	Dose rate per activity concentration	µSv h^{-1} per Bq g^{-1}	0.0E+00	FG12 [7], Tables 3.3 and 3.7
SKIN	Dose rate per activity concentration	Sv y^{-1}per Bq cm^{-2}	1.4E-04	No values in FG12 [7] or Kocher87 [8] or other publications consulted. Value assumed to be equal to value for ^{55}Fe. ^{55}Fe decays by electron capture with a higher probability of emission and a higher X-ray energy.

E.4.2 Ca-41 'out of scope' level

E.17   The results obtained using the spreadsheet for the eight scenarios, are given in Table E.9.

Table E.9. Results for Ca-41 obtained using the spreadsheet

Scenario	Dose per unit concentration of ^{41}Ca (µSv y^{-1}per Bq g^{-1})
EXT-A	0.00E+00
EXT-B	0.00E+00
EXT-C	0.00E+00
INH-A	4.10E-04
INH-B	8.83E-06
ING-A	5.80E-03
ING-B	5.20E-02
SKIN	4.31E-04
Maximum value	5.20E-02
Limiting scenario	ING-B

E.18   The scenario giving rise to the highest dose per unit concentration is ING-B. The dose per unit concentration for this scenario was compared with the RP122 Part 1 dose criterion of 10 µSv y^{-1} and this gave a corresponding unrounded 'out of scope' level of 192 Bq g^{-1}. The rounded 'out of scope' level is therefore 100 Bq g^{-1}.

E.19   These results are summarised in Table E.10.

Table E.10.   Summary of results for Ca-41

Radionuclide	Maximum dose per unit activity concentration ($\mu Sv\ y^{-1}$ per Bq g^{-1})	Unrounded 'out of scope' level (Bq g^{-1})	Rounded 'out of scope' level (Bq g^{-1})
Ca-41	5.20E-02	1.92E+02	100

E.20   This derived 'out of scope' level is considerably higher than the default value for radionuclides that are not listed in EPR2011, a value of 0.01 Bq g^{-1}, and reflects the fact that ^{41}Ca is an electron capture weak X-ray emitter. It is the same as the value for ^{55}Fe, another electron capture X-ray emitter.

E.21   IAEA have also calculated exclusion, exemption and clearance levels for a number of radionuclides [9]. Although the IAEA report does not specify an exclusion level for ^{41}Ca, the document describing the calculations [10] does give exclusion levels for ^{41}Ca for the 9 different scenarios considered. The water pathway scenario gives an exclusion level of 1000 Bq g^{-1} (see Table I-XIII of [10]) and the other 8 scenarios give an exclusion level of 100 Bq g^{-1} using realistic assumptions (see Table I-VII of [10]), and 100 Bq g^{-1} using low probability assumptions (see Table I-VIII of [10]). This suggests that the IAEA methodology gives an exclusion level of 100 Bq g^{-1} for ^{41}Ca.

E.5   Conclusions

E.22   A derived value of 100 Bq g^{-1} is presented as a more appropriate 'out of scope' level for ^{41}Ca than the default value of 0.01 Bq g^{-1} that is specified for radionuclides that are not listed in Table 2 of Schedule 23 of EPR2011.

E.6   References

1   EC. Radiation Protection 122. Part I: Guidance on General Clearance Levels for Practices. Recommendations of the Group of Experts established under the terms of Article 31of the Euratom Treaty. Directorate General, Environment, 2000.

2   EC. Recommended radiation protection criteria for the recycling of metals from the dismantling of nuclear installations. Radiation Protection No 89, 1998.

3   EC. Recommended radiological protection criteria for the clearance of buildings and building rubble from the dismantling of nuclear installations. Radiation Protection No 113, 2000.

4   Delacroix D, Guerre JP, Leblanc P and Hickman C. Radionuclide and Radiation Protection Data Handbook 2002. Radiation Protection Dosimetry Vol. 98 No 1, 2002.

5   ICRP Database of dose coefficients: Workers and Members of the Public. ICRP CD1 containing data from ICRP Publication 68 and ICRP Publication 72. http://www.icrp.org/publication.asp?id=ICRP CD1

6   IAEA. International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources. IAEA Safety Series No. 115, 1996.

7   Eckerman KF and Ryman JC. External exposure to radionuclides in air, water, and soil. Federal Guidance Report No.12, EPA-402-R-93-081, 1993.

8   Kocher DC and Eckerman KF. Electron dose-rate conversion factors for external exposure of the skin from uniformly deposited activity on the body surface. Health Physics Vol. 53, No.2, pp 135-141, 1987.

9   IAEA. Application of the Concepts of Exclusion, Exemption and Clearance. Safety
         Standards Series Safety Guide R-S-G1.7, 2004.

10   IAEA. Derivation of activity concentration values for exclusion, exemption and
         clearance. Safety Reports Series No. 44, 2005.

Appendix F   Derivation of Surface Clearance Levels for Contaminated Items

F.1   Background

F.1   Radionuclide specific surface clearance levels have been defined for recycling or reuse of metals arising from the dismantling of nuclear installations [1, 2] and for buildings and building rubble from the dismantling of nuclear installations [3, 4]. These surface clearance levels have been defined following the procedure as outlined in the main text:

- ◆ Choice of scenarios
- ◆ Definition of pathways of exposure
- ◆ Definition of parameter values
- ◆ Calculation of individual dose per unit surface activity concentration
- ◆ Establish limiting scenario and pathway
- ◆ Calculation of surface clearance levels based on a dose limit of 10 µSv per year

F.2   Clearance measurements regarding surface contamination are usually alpha contamination and beta contamination measurements using handheld monitors. The results of these measurements do not give specific activities per radionuclide but total alpha activity and total beta activity. In order to compare these results with the clearance levels, these latter need to be converted into relevant values by means of the radionuclide fingerprint.

F.3   This appendix illustrates the calculation of maximum alpha, beta and total activity levels for reuse of metallic equipment from dismantling of nuclear installations. Specific clearance levels per radionuclide have been collected from [2].   The fingerprint used for this exercise is collected from Table 9.2 from the main text.

F.4   The calculations have been undertaken using a simpleExcel spreadsheet. This spreadsheet is set up such that the general radionuclide fingerprint can easily be substituted with a specific radionuclide fingerprint that is more tailored to the considered site.

F.5   The remainder of this appendix is organised as follows. Section F.2 gives an overview of the methodology to determine specific surface clearance levels per radionuclide.   Section F.3 describes the radionuclide fingerprint used to perform the example calculation. Section F.4 explains the calculation of maximum alpha, beta and total activities.

F.2   Overview of the methodology to determine specific surface clearance levels per radionuclide

F.6   In this example the radionuclide specific surface clearance levels are based on reuse scenarios for cleared metallic equipment [2]. This chapter gives an overview of the relevant scenarios and pathways and explains how the corresponding dose estimates are calculated.

F.7   The relevant scenarios and pathways are [2]:

- ◆ Skin dose from the reuse of cleared equipment
- ◆ Dose from inadvertent ingestion incurred during the reuse of equipment
- ◆ External gamma dose incurred during the reuse of cleared equipment
- ◆ Inhalation dose incurred during normal use of cleared equipment
- ◆ Inhalation dose incurred during cleaning / sanding of cleared equipment
- ◆ Inhalation dose incurred during repair / scrapping of cleared equipment

F.8   The text in sections F.2.1 through to F.2.6 are reproduced from [2].

F.2.1 Skin dose from the reuse of cleared equipment

F.9   *During the reuse of a cleared item the contamination can be transferred to the skin and cause a beta skin dose. Radioactive decay during the first year of use has been taken into account since the contamination comes from a single item. The following equation is used to estimate the skindose from reuse of cleared items,*

$$H_{skin} = D_{skin} \cdot w_s \cdot \frac{S_C}{S_T} \cdot f_s \cdot t \cdot A \cdot \frac{\left(1 - e^{-\lambda t_a}\right)}{\lambda t_a}$$

F.10   *where the parameters have the following meaning,*

H_{skin} *(µSv/a)*	*whole body effective dose from skin contamination*
D_{skin} *(µSv/a)/(Bq/cm²)*	*skin dose coefficient for a skin depth of 7 mg/cm² [5]*
w_s	*ICRP 60 skin weighting factor (0.01) [6]*
S_C/S_T	*contaminated surface / total skin surface (0.1 m²/1 m²)*
f_s	*transfer from item to skin (0.01)*
f_a	*fraction of year exposed (1800 / 8760 = 0.205)*
A *(Bq/cm²)*	*surface activity (1 Bq/cm²)*
t_a *(a)*	*time during which the dose is received (1 a)*
λ *(1/a)*	*decay constant*

F.2.2 Dose from inadvertent ingestion incurred during the reuse of equipment

F.11   *An inadvertent ingestion dose during the reuse of a cleared item can occur when the contamination is transferred from the item to the mouth via the hands. The ingestion dose for reuse is calculated using the following equation, taking radioactive decay into account,*

$$H_{ing} = D_{ing} \cdot f_s \cdot I_r \cdot t \cdot A \cdot \frac{\left(1 - e^{-\lambda t_a}\right)}{\lambda t_a}$$

F.12   *where the parameters have the following meaning,*

H_{ing} *(µSv/a)*	*ingestion dose*
Ding (µSv/Bq)	*ingestion dose coefficient [7]*
fs	*transfer from item to skin (0.01)*
Ir (cm2/h)	*ingestion rate (1.25 cm2/h)*
t (h/a)	*exposure time (1800 h/a)*
A (Bq/cm2)	*surface activity (1 Bq/cm2)*
ta (a)	*time during which the dose is received (1 a)*
λ (1/a)	*decay constant*

F.2.3 External gamma dose incurred during the reuse of cleared equipment

F.13   *Different scenarios could be considered, one for each piece of potentially releasable equipment. To calculate all possible scenarios is an unrealistic approach and is inappropriate for deterministic calculations. Instead one scenario is chosen and is used to represent the many possible scenarios. In this study the tool cabinet scenario has been selected as an enveloping scenario. The geometry of the tool cabinet is estimated as*

- *2 panels (doors and back):   1 m x 2 m each*
- *6 shelves: 1 m x 0.4 m each*
- *2 sides: 2 m x 0.4 m each*

F.14   *The total amount of metal considered is 8 m². It is assumed that the person using the cabinet is effectively exposed to 4 m2 which represents the front and back of the cabinet. The external exposure from the tool cabinet is calculated with the following equation,*

$$H_{ext} = D_{ext} \cdot t \cdot A \cdot \frac{\left(1 - e^{-\lambda t_a}\right)}{\lambda t_a}$$

F.15   *where the parameters have the following meaning,*

H_{ext} *(μSv/a)*   external gamma dose
D_{ext} *(μSv/h)/(Bq/cm²)* external dose rate [Appendix of 2]
t (h/a)   exposure time (1800 h/a)
A (Bq/cm²)   surface activity (1 Bq/cm²)
t_a *(a)*   time during which the dose is received (1 a)
λ (1/a)   decay constant

F.16   *The calculation is based on 2 discs each having an area of 2 m². The effective distances from the discs are 1 m and 1.4 m and the exposure geometry is taken to be rotational. The exposure time is assumed to be 1800 h/a representing a full working year. Since the exposure is always to the same object the radioactive decay is accounted for in the dose calculations.*

F.2.4 Inhalation dose incurred during normal use of cleared equipment

F.17   *During the normal use of equipment activity in the surface layer can be shaken lose and resuspended. This is especially true for equipment like a truck, fork lift, crane or lathe and drill press. The following equation is used to estimate the dose from this scenario,*

$$H_{inh} = D_{inh} \cdot V \cdot \frac{A \cdot \varepsilon}{d \cdot \rho} \cdot C_D \cdot t \cdot \frac{\left(1 - e^{-\lambda t_a}\right)}{\lambda t_a}$$

F.18   *where the parameters have the following meaning,*

H_{inh} *(μSv/a)*   inhalation dose
D_{inh} *(μSv/Bq)*   ingestion dose coefficient [7]
V (m³/h)   surface activity (1.2 m³/h)
A (Bq/cm²)   surface activity (1 Bq/cm²)
ε   fraction of dust from the contaminated item (0.01)
d (cm)   effective thickness of re-suspended layer (20 μm)
ρ (g/cm³)   dust concentration (2 g/cm²)

C_D (g/m^3)   dust concentration (0.2 mg/m^3)
t (h/a)   exposure time (1800 h/a)
t_a (a)   time during which the dose is received (1 a)
λ (1/a)   decay constant

F.19   The dust concentration is taken to represent a year-long average and not peak concentrations [8]. Since the activity is surface bound activity, when it is re-suspended, the air carried fraction will obviously have a significantly higher mass specific activity than the original item.

F.2.5 Inhalation dose incurred during cleaning / sanding of cleared equipment

F.20   Equipment which is used after clearance is likely to be refurbished. This may include stripping the surface layer in preparation for a new coat of paint. In such a case the entire surface activity could be removed in a short amount of time. The following equation is meant to describe this,

$$H_{inh} = D_{inh} \cdot V \cdot \frac{A}{d \cdot \rho} \cdot C_D \cdot t$$

F.21   where the parameters have the following meaning,

H_{inh} (µSv/a)   inhalation dose
D_{inh} (µSv/Bq)   ingestion dose coefficient [7]
V (m^3/h)   surface activity (1.2 m^3/h)
A (Bq/cm^2)   surface activity (1 Bq/cm^2)
d (cm)   thickness of stripped layer (0.05 cm)
ρ (g/cm^3)   dust concentration (2 g/cm^2)
C_D (g/m^3)   dust concentration (5 mg/m^3)
t (h/a)   exposure time (20 h/a)

F.22   It is assumed that the entire air carried dust coming from the surface stripping activity. The background dust concentration (< 0.2 mg/m^3) represents only a fraction of the total dust concentration so that this assumption is appropriate. The concentration represents a level close to the maximum allowed level in working areas. The exposure time is estimated by assuming that 10 m^2 of surface are stripped at a rate of 0.5 m^2/h. This represents the work required for one large object like a truck.

F.2.6 Inhalation dose incurred during repair / scrapping of cleared equipment

F.23   The scrapping thermal segmentation scenario can be considered as the enveloping scenario since repair work such as welding will not affect as much the surface as segmenting and therefore not lead to as much re-suspended activity. The scrapping scenario assumes that a large piece of equipment is thermally segmented directly after being cleared, in which case radioactive decay is not a factor. The dose can be calculated using the following equation,

$$H_{inh} = D_{inh} \cdot V \cdot \frac{f_A \cdot S_r}{V_r \cdot E_r} \cdot t \cdot A$$

F.24   where the parameters have the following meaning,

H_{inh} (µSv/a)   inhalation dose
D_{inh} (µSv/Bq)   ingestion dose coefficient [7]
V (m^3/h)   surface activity (1.2 m^3/h)

f_a *(Bq/m)/(Bq/m²)*   *release per cut length normalised by the surface activity*
                          (3.3 (Bq/m)/Bq/m²))
S_r *(m/h)*   *segmenting rate (42 m/h)*
V_r *(m³)*   *volume of work hall (800 m³)*
E_r *(h⁻¹)*   *air exchange rate (8 h⁻¹)*
t *(h/a)*   *exposure time (2 h/a)*
A *(Bq/cm²)*   *surface activity (1 Bq/cm²)*

F.2.7 Radionuclide specific surface clearance levels

F.25   A range of radionuclides has been considered in [2].   For each of these radionuclides, doses due to all the above scenarios and pathways have been calculated and then the maximum dose was identified.

F.26   Table F.1 represents the results of the above described calculations.

Table F.1.   Unrounded and rounded surface clearance levels for reuse of metallic items [2]

Radionuclide	Maximum dose (uSv/a)/(Bq/cm2)	Most restrictive reuse scenario	Clearance level (Bq/cm2) unrounded	Clearance level (Bq/cm2) rounded
H-3	3.90E-04	ingestion (reuse)	2.50E+04	10000
C-14	1.30E-02	ingestion (reuse)	7.70E+02	1000
Na-22	8.80E+00	external (reuse)	1.10E+00	1
S-35	5.70E-03	ingestion (reuse)	1.80E+03	1000
Cl-36	5.70E-03	skin (reuse)	1.50E+01	10
Ca-45	8.70E-03	ingestion (reuse)	1.20E+03	1000
Sc-46	2.90E+00	external (reuse)	3.40E+00	10
Mn-53	6.70E-04	ingestion (reuse)	1.50E+04	10000
Mn-54	2.70E+00	external (reuse)	3.70E+00	10
Fe-55	6.50E-03	ingestion (reuse)	1.50E+03	1000
Co-56	4.70E+00	external (reuse)	2.10E+00	1
Co-57	3.30E-01	external (reuse)	3.00E+01	10
Co-58	1.20E+00	external (reuse)	8.00E+00	10
Co-60	1.00E+01	external (reuse)	1.00E+00	1
Ni-59	1.40E-03	ingestion (reuse)	7.10E+03	10000
Ni-63	3.40E-03	ingestion (reuse)	3.00E+03	1000
Zn-65	1.60E+00	external (reuse)	6.30E+00	10
As-73	8.90E-03	external (reuse)	1.10E+03	1000
Se-75	7.20E-01	external (reuse)	1.40E+01	10
Sr-85	6.20E-01	external (reuse)	1.60E+01	10
Sr-90	6.90E-01	ingestion (reuse)	1.50E+01	10
Y-91	1.20E-02	ingestion (reuse)	8.10E+02	1000
Zr-93	3.50E-02	inhalation (sanding)	2.90E+02	100
Zr-95	2.80E+00	external (reuse)	3.60E+00	10
Nb-93m	9.80E-03	external (reuse)	1.00E+03	1000
Nb-94	7.40E+00	external (reuse)	1.40E+00	1
Mo-93	5.80E-02	ingestion (reuse)	1.70E+02	100

Derivation of Surface Clearance Levels for Contaminated Items

Radionuclide	Maximum dose (uSv/a)/(Bq/cm2)	Most restrictive reuse scenario	Clearance level (Bq/cm2) unrounded	Clearance level (Bq/cm2) rounded
Tc-97	6.50E-02	external (reuse)	1.50E+02	100
Tc-97m	1.80E-02	external (reuse)	5.60E+02	1000
Tc-99	1.80E-02	skin (reuse)	5.70E+02	1000
Ru-106	7.10E-01	external (reuse)	1.40E+01	10
Ag-108m	7.70E+00	external (reuse)	1.30E+00	1
Ag-110m	8.00E+00	external (reuse)	1.30E+00	1
Cd-109	1.10E-01	external (reuse)	9.10E+01	100
Sn-113	5.50E-01	external (reuse)	1.80E+01	10
Sb-124	1.90E+00	external (reuse)	5.10E+00	10
Sb-125	1.90E+00	external (reuse)	5.20E+00	10
Te-123m	2.70E-01	external (reuse)	3.70E+01	100
Te-127m	3.40E-02	external (reuse)	3.00E+02	100
I-125	8.10E-02	ingestion (reuse)	1.30E+02	100
I-129	2.50E+00	ingestion (reuse)	4.00E+00	10
Cs-134	6.20E+00	external (reuse)	1.60E+00	1
Cs-135	4.50E-02	ingestion (reuse)	2.20E+02	100
Cs-137	2.70E+00	external (reuse)	3.70E+00	10
Ce-139	3.30E-01	external (reuse)	3.00E+01	10
Ce-144	1.50E-01	external (reuse)	6.80E+01	100
Pm-147	9.70E-03	skin (reuse)	1.00E+03	1000
Sm-151	3.10E-03	inhalation (sanding)	3.20E+03	10000
Eu-152	5.10E+00	external (reuse)	2.00E+00	1
Eu-154	5.50E+00	external (reuse)	1.80E+00	1
Eu-155	2.50E-01	external (reuse)	4.10E+01	100
Gd-153	3.20E-01	external (reuse)	3.10E+01	10
Tb-160	1.40E+00	external (reuse)	7.30E+00	10
Tm-170	1.50E-02	skin (reuse)	6.60E+02	1000
Tm-171	3.10E-03	skin (reuse)	3.20E+03	10000
Ta-182	2.40E+00	external (reuse)	4.20E+00	10
W-181	7.30E-02	external (reuse)	1.40E+02	100
W-185	5.20E-03	skin (reuse)	2.00E+03	1000
Os-185	1.10E+00	external (reuse)	8.70E+00	10
Ir-192	1.10E+00	external (reuse)	9.20E+00	10
Tl-204	3.20E-02	skin (reuse)	3.10E+02	100
Pb-210	1.50E+01	ingestion (reuse)	6.60E-01	1
Bi-207	7.00E+00	external (reuse)	1.40E+00	1
Po-210	2.60E+00	inhalation (sanding)	3.80E+00	10
Ra-226	7.80E+00	external (reuse)	1.30E+00	1
Ra-228	1.40E+01	ingestion (reuse)	7.00E-01	1
Th-228	4.10E+01	inhalation (sanding)	2.40E-01	0.1
Th-229	9.60E+01	inhalation (sanding)	1.00E-01	0.1
Th-230	3.40E+01	inhalation (sanding)	3.00E-01	0.1

Radionuclide	Maximum dose (uSv/a)/(Bq/cm2)	Most restrictive reuse scenario	Clearance level (Bq/cm2) unrounded	Clearance level (Bq/cm2) rounded
Th-232	3.50E+01	inhalation (sanding)	2.90E-01	0.1
Pa-231	1.10E+02	inhalation (sanding)	9.40E-02	0.1
U-232	3.10E+01	inhalation (sanding)	3.20E-01	1
U-233	8.30E+00	inhalation (sanding)	1.20E+00	1
U-234	8.20E+00	inhalation (sanding)	1.20E+00	1
U-235	7.30E+00	inhalation (sanding)	1.40E+00	1
U-236	7.60E+00	inhalation (sanding)	1.30E+00	1
U-238	6.80E+00	inhalation (sanding)	1.50E+00	1
Np-237	1.80E+01	inhalation (sanding)	5.60E-01	1
Pu-236	1.60E+01	inhalation (sanding)	6.40E-01	1
Pu-238	3.60E+01	inhalation (sanding)	2.80E-01	0.1
Pu-239	3.80E+01	inhalation (sanding)	2.60E-01	0.1
Pu-240	3.80E+01	inhalation (sanding)	2.60E-01	0.1
Pu-241	7.00E-01	inhalation (sanding)	1.40E+01	10
Pu-242	3.70E+01	inhalation (sanding)	2.70E-01	0.1
Pu-244	3.60E+01	inhalation (sanding)	2.80E-01	0.1
Am-241	3.20E+01	inhalation (sanding)	3.10E-01	0.1
Am-242m	2.90E+01	inhalation (sanding)	3.50E-01	1
Am-243	3.20E+01	inhalation (sanding)	3.10E-01	0.1
Cm-242	4.40E+00	inhalation (sanding)	2.30E+00	1
Cm-243	2.40E+01	inhalation (sanding)	4.20E-01	1
Cm-244	2.00E+01	inhalation (sanding)	4.90E-01	1
Cm-245	3.20E+01	inhalation (sanding)	3.10E-01	0.1
Cm-246	3.20E+01	inhalation (sanding)	3.10E-01	0.1
Cm-247	3.00E+01	inhalation (sanding)	3.30E-01	1
Cm-248	1.10E+02	inhalation (sanding)	8.80E-02	0.1
Bk-249	1.20E-01	inhalation (sanding)	8.30E+01	100
Cf-248	7.30E+00	inhalation (sanding)	1.40E+00	1
Cf-249	5.40E+01	inhalation (sanding)	1.90E-01	0.1
Cf-250	2.60E+01	inhalation (sanding)	3.80E-01	1
Cf-251	5.50E+01	inhalation (sanding)	1.80E-01	0.1
Cf-252	1.60E+01	inhalation (sanding)	6.40E-01	1
Cf-254	2.60E+01	inhalation (sanding)	3.80E-01	1
Es-254	7.20E+00	inhalation (sanding)	1.40E+00	1

F.3   Definition of the fingerprint

F.27   It is common practice within the nuclear industry to establish approximate ratios of radionuclides within the radioactive material in order to facilitate later assessment of the activity within discrete articles or substances. A comprehensive list of the radionuclides that are likely to be present in the waste or material, and their relative contributions to the total activity, is commonly known as a *fingerprint*. An illustrative fingerprint is presented in Table F.2 below. Note that the precision with which the

results are quoted is far better than any credible measurement uncertainty and is used, in this illustration, to make the sum = 1.

Table F.2.   Illustrative fingerprint

Alpha-emitting radionuclides	Percentage of total activity	Beta-emitting radionuclides	Percentage of total activity
^{238}Pu	1.82	^{241}Pu	45.0
^{239}Pu	1.37	^{137}Cs	27.0
^{240}Pu	2.39	^{90}Sr	10.0
^{241}Am	2.80	^{147}Pm	3.64
^{242}Cm	0.08	^{154}Eu	1.09
^{244}Cm	0.64	^{155}Eu	1.09
		^{151}Sm	1.18
		^{134}Cs	0.99
		^{60}Co	0.91
Alpha	9.1	Beta	90.9
Alpha:Beta ratio: 1:10			
Reference Date: XXXXX			
Reference Number: BXXX/FP/999			

F.28   Fingerprints are used to infer the activities of radionuclides that cannot be conveniently measured directly, based on information about the radionuclides potentially present. Provided it is valid to establish and use fingerprints in support of overall activity assessments, their application simplifies the process of classifying wastes or materials. Requirements for detailed monitoring and/or analysis will be less intensive since application of fingerprints avoids the need to independently measure all radionuclides in each volume of radioactive material sentenced. Thus, the time and cost associated with characterisation will be reduced.

F.29   The fingerprint should regularly be evaluated. In particular if the Alpha:Beta ratio measured for the item would not match the fingerprint, this would be an indication that the fingerprint might not be suitable.

F.4   Calculation of the maximum alpha, beta and total activity levels

F.30   The fingerprint from section F.3 was used to determine maximum alpha, beta and total activities. This was done by applying the "sum of quotients" rule,

$$\sum_i \frac{a_i}{m_i} < 1$$

F.31   where the parameters have the following meaning,

   a_i *(Bq/cm^2)   surface activity for radionuclide i*
   m_i *(Bq/cm^2)   maximum surface activity for radionuclide i*

F.32   The maximum activity for a set radionuclide fingerprint is therefore determined by the following equation,

$$M = \left(\sum_i \frac{p_i}{m_i} \right)^{-1} \times \sum_i p_i$$

F.33   *where the parameters have the following meaning,*

   M *(Bq/cm^2)*   *maximum total surface activity for the considered radionuclides*
   p_i *percentage of the fingerprint for radionuclide i*
   m_i *(Bq/cm^2)*   *maximum surface activity for radionuclide i*

F.34   The radionuclides of concern are alpha emitters, beta emitters or alpha and beta emitters. The limits were calculated with both unrounded and rounded results for individual radionuclides (see Table F.3).

Table F.3. Maximum surface activity values for alpha emitters, beta emitters and alpha and beta emitters (Bq/cm^2).

	Limits based on unrounded results	Limits based on rounded results
Alpha (Bq/cm^2)	0.29	0.11
Beta (Bq/cm^2)	6.81	8.11
Alpha + Beta (Bq/cm^2)	2.24	1.04

F.35   The limits for alpha and beta emitters presented above were determined on the basis that only alpha or beta emitters were present in the radionuclide fingerprint. This would mean that the fingerprint would not correspond to the fingerprint presented in Table F.2 and the values are presented for illustrative purposes only.

F.5   References

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         Band 47 Nr. 1-2, Springer-Verlag, 1987.

Appendix G   Clearance and Exemption Working Group 2011-2012

Name	Company
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