Unclassified **NEA/RWM/WPDD(2013)2**

Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development **18-Oct-2013**

English - Or. English

NUCLEAR ENERGY AGENCY
RADIOACTIVE WASTE MANAGEMENT COMMITTEE

NEA/RWM/WPDD(2013)2
Unclassified

Working Party on Decommissioning and Dismantling (WPDD)

Radiological Characterisation for Decommissioning of Nuclear Installations

Report of the Task Group on Radiological Characterisation and Decommissioning (RCD) of the Working Party on Decommissioning and Dismantling (WPDD)

Final Report
September 2013

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JT03346655

English - Or. English

Radioactive Waste Management

Radiological Characterisation for Decommissioning of Nuclear Installations

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 34 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

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NUCLEAR ENERGY AGENCY

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The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as

– to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information.

The NEA Data Bank provides nuclear data and computer program services for participating countries. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

Foreword

Radiological characterisation is critical to inform decision making and investments during all phases of the life cycle of a nuclear installation. There are different considerations for design, construction, operation, transition, decommissioning – the major waste management challenge – and finally site release. Radiological characterisation to support the decommissioning process is required with different aims and intensity throughout the different phases, but in particular during the transition phase when operation has ceased, and during the implementation of decommissioning.

This report provides guidance on selection and tailoring strategies for radiological characterisation, and gives an overview of best practice for radiological characterisation at different phases of the life cycle of a nuclear installation.

Author Acknowledgements

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Yvon Desnoyers – Geovariances

Catherine Olivier Dehaye – EDF

Frédéric Tardy – EDF

Germany

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Executive Summary

Radiological characterisation plays an important role in the decommissioning of nuclear facilities. It is the basis for radiation protection, identification of contamination, assessment of potential risks, cost estimation, planning and implementation of decommissioning and other matters. At all stages of a decommissioning project, adequate radiological characterisation is of crucial importance.

The focus of this report is the task of radiological characterisation. The important role and the significance of radiological characterisation become clear when its various objectives are considered, including in particular:

- determination of the type, isotopic composition and extent of contamination in structures, systems, components and environmental media;
- identification of the nature and extent of remedial actions and decontamination;
- supporting planning of decommissioning;
- estimation of decommissioning costs.

A large number of measurement techniques are available for successful application of radiological characterisation, allowing rapid and comprehensive determination of the activities of most relevant radionuclides. For other radionuclides that are hard to detect, scaling factors can be established that relate their activities to key nuclides.

Radiological characterisation is relevant in all phases of the life cycle of a nuclear installation, albeit with different levels of detail and with differing objectives. Basically, the following characterisation phases can be distinguished: pre-operational characterisation; characterisation during operation; characterisation during the transition phase (after final shutdown before initiation of dismantling); characterisation during dismantling (including remediation and decontamination); and characterisation to support the final status survey for site release.

The most comprehensive characterisation campaigns are usually carried out during the transition phase in preparation for implementation of dismantling activities, or during the dismantling phase where systems, structures, components and buildings have to be characterised for decisions regarding the extent of decontamination, application of appropriate dismantling techniques, identification, classification, treatment of radioactive materials, etc. The final status survey on the site has quite distinctive features as it also has to take into account the possibility of subsurface contamination, which may lead to radionuclide transfer into ground water and surface water bodies.

Careful planning and implementation of radiological characterisation campaigns will allow significant reduction of time, costs and effort. On a strategic and managerial level, there are ways to maximise the efficiency of measurement techniques (e.g. by combining several types of measurement and sampling approaches) to increase efficiency of characterisation (e.g. by integrating characterisation into other tasks), or to choose an optimum form of organisation by allocating staff and resources timely and adequately to achieve the required characterisation results when needed, thus avoiding delays in the normal decommissioning workflow or radioactive waste management.

Today, experience gained from a large number of decommissioning projects helps to implement radiological characterisation effectively. Radiological characterisation is undoubtedly one of the key factors for any successful decommissioning project.

1. Introduction

Background

Radiological characterisation plays an important role in decommissioning of nuclear facilities. It is the basis for planning, identification of the extent and nature of contamination, assessing potential risk impacts, cost estimation, implementation of decommissioning framework, radiation protection, protection of the environment, and management of material arising from decommissioning, as well as supporting decisions for release of buildings and site.

Due to the important role and significance of characterisation through all phases of decommissioning projects, the Working Party on Decommissioning and Dismantling (WPDD) of the Nuclear Energy Agency (NEA) of the OECD decided to initiate a Task Group on Radiological Characterisation and Decommissioning (RCD).

The main objective was to develop a status report on the selection and tailoring of strategies for radiological characterisation and their importance for safe and efficient decommissioning of nuclear facilities. This document provides guidance on the implementation of strategies for radiological characterisation. The importance of radiological characterisation for all phases of a nuclear facility's life cycle must not be underestimated.

Aims and objectives

The aim of this report is to identify and give an overview of the best practice for radiological characterisation at different stages of decommissioning and to point out areas that could or should be developed further through international co-operation and co-ordination.

The audience for this report is decision makers, and in general those that are involved in planning, preparation and/or performance of decommissioning of nuclear installations. The report summarises various issues relating to radiological characterisation in a short and succinct way, giving an overview of the issues, the techniques, possible obstacles, strategic aspects and lessons learned. The reader interested in more in-depth or detailed information should consult the documents listed in the bibliography.

Scope

The present report covers important aspects relating to radiological characterisation of nuclear installations with respect to decommissioning; it does not cover survey methods for clearance of materials and buildings or the release of sites. Brief outlines of the scope of each chapter are presented below:

- Chapter 2 describes the role and significance of radiological characterisation in decommissioning to provide an overview of this task, in particular with respect to the applied methods and its significance for a decommissioning project.

- Chapter 3 gives an overview on radiological characterisation during the various phases of a nuclear installation's life cycle and discusses how synergies with respect to efficient radiological characterisation can be exploited between various phases.
- Chapter 4 presents implementation issues for a typical radiological characterisation campaign. Practical information for implementing radiological characterisation in an efficient way is provided.
- Chapter 5 discusses overarching aspects that are relevant to all phases and that have more strategic importance. This chapter includes discussion of staff and organisational aspects, aspects related to performance of measurement and measurement strategies, use of integrated approaches and of issues/obstacles that have the potential to cause significant delays and increasing the costs.
- Chapter 6 provides a list of important lessons that have been learned from a multitude of decommissioning projects.
- Chapter 7 offers a short overview of areas suitable for further study, e.g. by OECD/NEA Task Groups.
- The reference list indicates sources that are directly referred to in the text. The bibliography section at the end of the document provides suggestions for further reading.
- Appendices provide information on the implementation of sampling strategies and requirements.
- The glossary explains some terms that may not be common in radiation protection literature or that have a special meaning in this report.

2. Role and Significance of Radiological Characterisation in Decommissioning, and Some Key Aspects of its Implementation

Radiological characterisation

In general, the term "radiological characterisation" represents the determination of the nature, location and concentration of radionuclides at a nuclear installation. It is one of the fundamentals on which to build a decommissioning project. Radiological characterisation must be seen as an ongoing process and will only cease after successful execution of the final survey and the termination of the nuclear license. It does not only consist of sampling and measurements and analyses of the results, but will also involve evaluation of information from the operating history, from calculations, from collections of existing data and many more sources.

When a nuclear installation is about to be shut down permanently, a radiological characterisation programme should be established as soon as possible. It should define the principles, methods and steps necessary for the determination of the residual activity in all relevant media and structures, providing a reliable database of information on quantity and type of radionuclides, and their physical and chemical states.

Radiological characterisation with respect to decommissioning shall mainly accomplish the following general objectives:

- Determine the type, isotopic composition or mixtures and extent of contamination in structures, systems, components and environmental media.
- Verify activation calculations.
- Quantify hard to detect nuclides.
- Support dose modelling to develop dose-based clearance and release criteria for materials, buildings and the site.
- Support assessment of decontamination techniques.
- Determine waste classifications for packaging, shipping and disposal.
- Determine which remedial actions will be needed, including the extent of decontamination that will be required.
- Provide dose assessments for the workers during the implementation of decommissioning.
- As the input data for the safety analysis of the decommissioning operations, support an impact assessment due to decommissioning operations and accidental situations, and underpin decisions about the types of safety and radiological protection required for the protection of workers, the general public and the environment.
- Support the estimate of decommissioning costs.
- Verify that the facility and the site will ultimately meet release criteria.

Application of radiological characterisation in the various phases of the life cycle of a nuclear installation

The life cycle of a nuclear installation will comprise various phases, from planning and the construction phase, then operation up to the transition phase, followed by dismantling and site release. Radiological characterisation is required with different aims and varying intensity throughout all these phases, but in particular during the transition phase and the implementation of decommissioning. Typical objectives during these phases include:

- *During the siting phase:* Baseline surveys are undertaken to determine background radiation levels.
- *During the construction phase:* Construction materials are retained to support future activation calculations and to define the natural activity background (uranium, thorium, ^{40}K).
- *During the operational phase:* Surveys are done regularly for establishing dose rate and contamination levels, with additional surveys and measurements being required following incidents involving plant contamination.
- *During the transition phase:* Detailed radiological surveys and measurements are required to support the development of the final decommissioning plan.
- *During dismantling:* Radiological characterisation goes hand in hand with all issues of safety and dose assessment, radioactive waste management, clearance of materials and buildings, etc.
- *During license termination (closure) phase:* A final survey of the site and any remaining structures will be needed to support an application for release of the site from regulatory control.

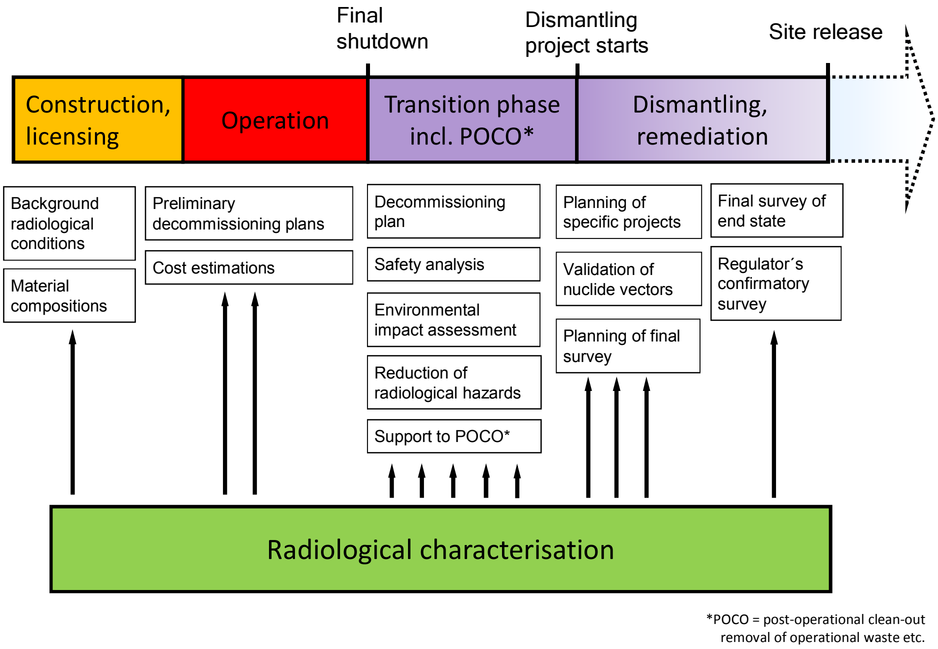
This is schematically illustrated in Figure 2.1. A more in-depth discussion can be found in Chapter 3.

Characterisation as an important input for estimation of costs and liabilities

Radiological characterisation is also an important input for the estimation of costs and liabilities for a decommissioning project. It is the responsibility of the operator of a nuclear installation to estimate the required costs for carrying out decontamination and decommissioning including radioactive waste management, and many countries even have strict rules on reliable and precise estimations of liabilities and secure protection of the corresponding assets, including monetary funds. Informed decisions can only be based on a proper radiological characterisation.

Radiological characterisation plays a central role in the development of the decommissioning planning and by then is a key parameter for the estimation of the required funding for the decommissioning of a nuclear installation. Radiological characterisation helps to identify and estimate a large number of parameters relevant to decommissioning and management of radioactive material, as has been pointed out in previous sections and will be dealt with throughout this report. Keeping in mind that each of these parameters (like the amount of decontamination that will be required, the quantities of radioactive waste and of material eligible for clearance, the decision whether to apply costly remote-controlled or manual dismantling techniques, etc.) is associated with a large uncertainty of costs, it becomes clear that a thorough radiological characterisation, which forms a solid base for all aspects of decommissioning planning, also facilitates cost estimations. Many fields where radiological characterisation is linked to strategic or managerial aspects are discussed in Chapter 5. This includes considerations

Figure 2.1: Radiological characterisation efforts as needed during all stages of a nuclear facility's life cycle, in order to plan and perform decommissioning in a safe and efficient manner



with respect to the end-state of the facility, i.e. whether it will be possible to release the site with or without restrictions, which may influence decisions about long-term liabilities that may be substantial in comparison to the costs for decommissioning to green-field status. It should be noted that cost estimations are based on many additional factors, including characterisation for conventional (non-radiological) hazards in nuclear facilities, etc.

Implementation of radiological characterisation

Radiological characterisation needs careful planning and a dedicated infrastructure as well as knowledgeable staff for its implementation. A comprehensive radiological characterisation programme or campaign normally comprises the following steps:

- An initiating step where the targets of the campaign are defined and, if necessary, where consent from the competent authority is gained.
- A planning step where historical information from the facility is evaluated and where the strategy and the plan for sampling and measurements are developed.
- An implementation step where sampling and measurements are carried out, if necessary aided by calculation methods, e.g. for determination of activation.
- A step for data assessment and evaluation, in which the various results are interpreted and reviewed, statistical evaluation of measurement results is carried out, etc., and where calculated results and measured data are compared.
- A finalisation step where the results are documented and (if necessary) reported to the competent authority and are used for the various purposes and objectives for which they have been derived.

A more in-depth discussion of such a radiological characterisation programme is presented in Chapter 4.

Techniques used in radiological characterisation

There are a large number of technical procedures for carrying out radiological characterisation, in particular:

- Taking samples according to sampling plan, which are subsequently analysed by various measurement methods. Samples can be taken with mechanical tools from surfaces, by drilling core samples from volumes, or with many other techniques from various depths of the material to be analysed (metal, building surfaces, rubble, soil, etc.).
- Methods for analysis of samples comprise among other things laboratory gamma spectrometry or alpha/beta spectrometry after radiochemical separation as well as gross alpha/gross beta measurements, both in-field or in laboratories.
- In addition to sampling, measurements of the dose rate, the gross alpha, beta and/or gamma contamination can be carried out *in situ*.
- A full account of the gamma-emitting radionuclides can usually be measured with *in situ* gamma spectrometry. Further, key nuclides to which hard-to-measure nuclides can be correlated can be selected and analysed to reflect levels of contamination of these hard-to-measure nuclides.
- The results obtained from the sampling and measurement programme are usually complex and need to be analysed and evaluated by various mathematical methods. They are therefore usually managed in databases that will provide the different tools for statistical data evaluation.

These procedures are further discussed in Chapter 5, under *Measurement and sampling aspects*.

Due to lack of knowledge and inherent uncertainty of the quantities being measured prior to characterisation, ensuring the safety of workers undertaking radiological characterisation is an important consideration. This aspect may lead to increasing reliance on use of automated and remote techniques such as the use of robotics (in particular in the case of hot cells, in highly contaminated areas or at highly activated structures).

Definition of clear objectives for radiological characterisation

It is crucial to carry out measurements of samples and direct measurements in such a way that the data obtained from these measurements will be meaningful and serve the purposes they were collected for. This means that the data quality and quantity need to be assessed to meet the objectives of the required data.

The approach for defining clear objectives can follow a structured sequence of seven steps:

1) *State the problem*. Concisely describe the problem to be studied. Review prior studies and existing information to gain a sufficient understanding to define the problem.
2) *Identify the decision*. Identify what questions the radiological characterisation campaign will attempt to resolve, and what actions may result.
3) *Identify inputs to the decision*. Identify the information that needs to be obtained and the measurements that need to be taken to resolve the decision statement.
4) *Define the boundaries of the radiological characterisation campaign*. Specify the time periods and spatial area to which decisions will apply. Determine when and where data should be collected.

5) *Develop a decision rule*. Define the parameter of interest, e.g. the specific activities of a set of radionuclides, and specify appropriate activity levels that need to be reached during the measurements. The decision whether a particular measurement during radiological characterisation has been successful can then be based on compliance with these pre-defined activity levels.

6) *Specify limits on decision errors*. Define the tolerable decision error rates based on a consideration of the consequences of making an incorrect decision, e.g. with respect to the numbers of samples analysed or measurements, the detection limits, the radionuclides included in the evaluation, etc.

7) *Optimise the survey design*. Evaluate information from the previous steps and generate alternative data collection designs for any subsequent radiological characterisation campaigns. Choose the most resource-effective design that meets all objectives. The data that are obtained should in any case be representative, compatible with the objectives and complete.

Planning radiological characterisation using this stepwise procedure, which is often referred to as the “DQO process” (DQO = Data Quality Objectives) can improve the survey effectiveness and efficiency, and thereby the defensibility of decisions (US EPA, 2006). It can also minimise expenditures and time related to data collection by eliminating unnecessary, duplicative or overly precise data.

The DQO process is an example of a systematic approach that assures that the type, quantity and quality of data used in decision making will be appropriate for the intended application. It provides procedures for defining the criteria that the survey design should satisfy, including when and where to perform measurements, the level of decision errors for the survey and the number of measurements to perform.

3. Radiological Characterisation During the Various Phases of a Nuclear Installation

While it has already been stated in Chapter 2 that radiological characterisation is important in all phases of the life cycle of a nuclear installation, in particular before and during dismantling, the objectives of radiological characterisation will change along with the progress of the decommissioning project. This chapter describes the phases of radiological characterisation and their synergies with the life cycle phases of the nuclear facility. In this context, the following characterisation phases can be distinguished:

- pre-operational characterisation;
- characterisation during operation;
- characterisation during the transition phase (after final shutdown before initiation of actual dismantling);
- characterisation during dismantling (including remediation and decontamination);
- characterisation to support the final status survey for site release.

A summary of the main activities in association with the life cycle of a nuclear installation is presented in the following sections.

Coupling and synergies between radiological characterisation in different phases

A plan for characterisation actions aiming for safe, timely and cost effective decommissioning should ideally be drafted early in the life cycle of a facility. This plan should cover couplings and synergies of various aspects regarding what and how to do during each phase as well as what information from earlier phases can be used afterwards in later phases.

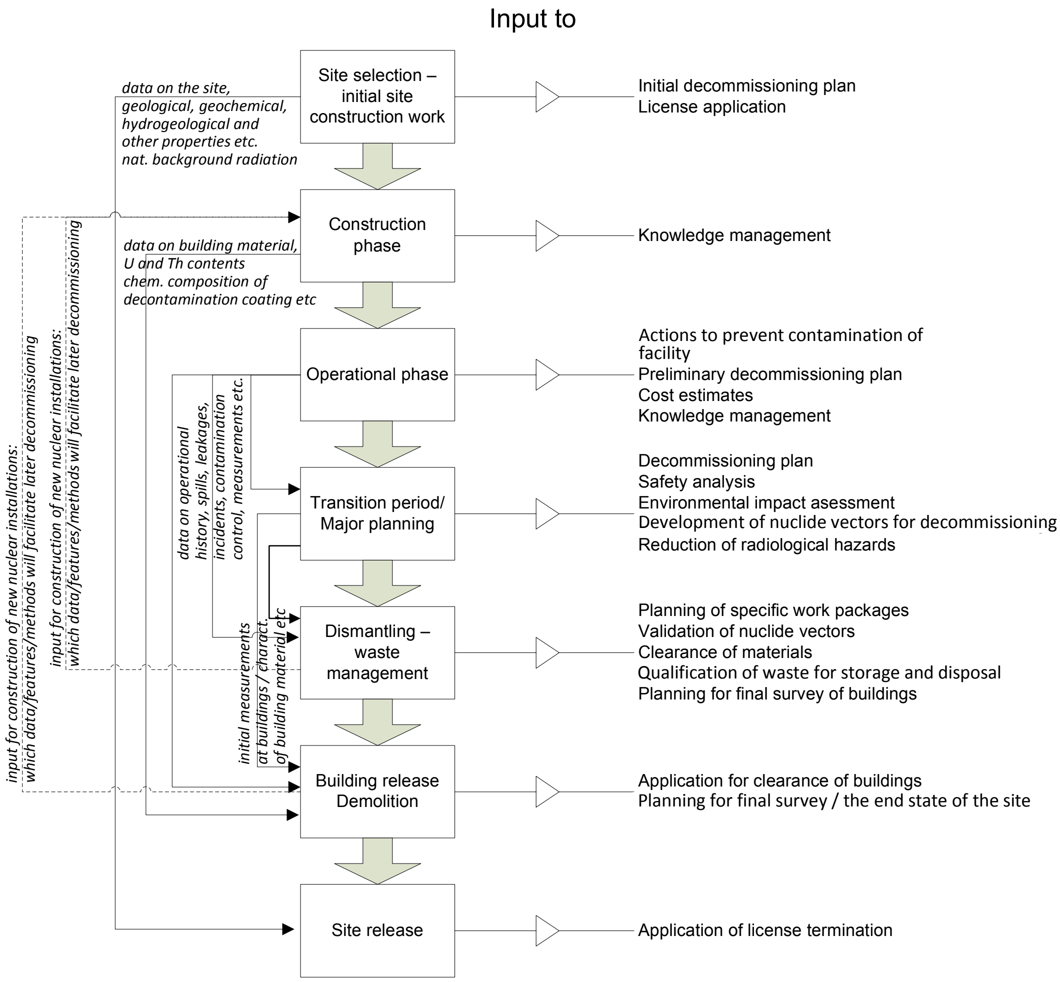
For example, during the operational phase radiological characterisation could mainly focus on providing information from the periodic radiation protection control activities and observations from normal operational data (e.g. environmental monitoring data and normal releases as specified under license conditions), as well as incidents such as spillages or uncontrolled leakages. At later phases of the operational lifetime before final shutdown, more precise information, from a decommissioning perspective, will be required for specific planning purposes. It is quite evident that there are built-in synergies between characterisation phases and facility life cycle phases. It is widely recognised that a great deal of information covering the entire life cycle of the facility should be collected throughout facility life cycle, and made available through appropriate record keeping, to support decommissioning characterisation schemes. Such information should be adequately analysed and managed properly.

A successful decommissioning project requires certain major decisions in the earlier phases. These include assessment of decommissioning options, evaluation and selection of technologies (decontamination and dismantling, conditioning of activated material, etc.), establishment of conditions for clearance of materials and buildings and for site release, exploration of waste disposal options, plans for the transition phase (the intermediate phase between operation and decommissioning), conceptual cost estimates and schedules, waste generation and disposition estimates, and exposure estimates to workers and the public. Each of these decisions needs to be informed by the results of radiological characterisation. Several factors must be evaluated to determine the scope of a decommissioning project, such as:

- site historical data and information;
- initial site and facility configuration and characterisation;
- initial project limits and contents;
- final site configuration;
- final site boundary;
- expected clearance criteria for materials and buildings and release criteria for sites.

However, data that has been gathered in an earlier phase may be needed again in a later phase of the decommissioning project. Thus, there are couplings and synergy effects between radiological characterisation in different phases which are schematically depicted in Figure 3.1.

Figure 3.1: Radiological characterisation – phases in a plant life cycle perspective



The arrows on the right side of Figure 3.1 indicate typical areas where radiological characterisation and characterisation of other properties of the nuclear facility will inform clean-up and decontamination activities as well as radioactive waste management, clearance and release of the site.

The arrows on the left side of Figure 3.1 indicate areas where information and data should be passed from one phase to another one to make maximum use of the available data. For example, if material samples of the building structure have been retained from the construction phase or if a thorough chemical analysis has been performed of that time, then the average U and Th content and thus the natural activity of the building material can be derived, allowing correction of measurements for this background value. Likewise, data on dose rates and surface contamination from routine measurements during the operational phase form a valuable input for setting up a characterisation programme in the transition phase and later for characterisation of materials with respect to management of radioactive materials.

Other examples where previously obtained data can later be used again include data on fuel element failures, derived from the measurements of alpha activity in the primary circuit during operation, or on the chemical composition of metallic material and concrete for activation calculations (reactor pressure vessel, reactor internals, biological shield and other structural material near the reactor core).

Radiological characterisation before and during operation

Characterisation consideration should begin very early. During the design and construction of a nuclear installation certain characterisation steps should be taken in order to simplify the decommissioning process and acquire necessary data to ultimately support site release. Such data could cover a variety of information needs from the initial properties and characteristics of the site to the composition of the construction materials, including structural features and foundation design, subsurface media characteristics and infrastructural properties (e.g. samples of construction materials can be taken in order to precisely determine a chemical composition for future activation calculations).

During operation, characterisation should be performed to follow the radiological status of the plant both over a short perspective (e.g. what actions are to be taken to avoid unnecessary contamination to the personnel) and over a longer perspective. An example for the latter is for the estimation of tramp uranium on the core surfaces through characterisation of the radioactivity caught in the filter system.

In particular, there are certain hard-to-measure nuclides such as ^{36}Cl or ^{90}Sr that cannot be measured directly through gamma radiation but can be fairly well estimated by measurement of short-lived gamma-emitting "surrogate nuclides" (e.g. ^{38}Cl as a surrogate for ^{36}Cl) or can be correlated to easy-to-measure key nuclides like ^{60}Co and ^{137}Cs, if the scaling factor is appropriately determined from radiological characterisation (with due consideration of radioactive decay).

The characterisation programme should be started as early as possible during the operational phase, but at the latest when the date of the definitive shutdown has been established. At this stage, it is best practice to draft an entire decommissioning plan, which also needs to be supported by a plan for radiological characterisation. Several factors must at this stage be evaluated to determine the scope of the forthcoming decommissioning project. This includes initial site and facility characterisation including the radiological conditions, expected waste arising from decommissioning activities, and the expected release criteria of residual radioactivity to be complied with at the end of the decommissioning project.

At the initial planning phase, it is essential to establish a clear understanding of how structures, systems, components, buildings and grounds are to be dismantled. The facility and site characterisation information regarding radiological as well as hazardous materials will be extremely valuable to evaluate, particularly when making these plans. It may be obvious that certain components and soil areas cannot be removed in a conventional manner due to levels of radioactivity that may expose workers to high radiological risks or cause spread of contamination. To reach such decisions, the characterisation surveys should be sufficiently detailed to support early strategy decisions on how to manage structures, components, buildings and/or soil.

The characterisation programme needs to be supported by a historical site assessment which can be described as an effort to collect as much information on the plant and site as possible. Reviewing the historical records such as licensing documents, periodic reports (environmental surveillance, ground water surveillance, etc.), radiological monitoring records, operating events (leakages, releases, etc.), pictures, drawings, construction records, operational procedures, visual inspections, contact and interviews, etc., of a facility constitutes the first activity in the characterisation project and provides a valuable knowledge of possible radiological conditions present for the planning of the physical and radiological characterisation programme. The main objectives of this characterisation are to:

- Identify potentially radiologically impacted structures, components, systems and areas inside and outside buildings.
- Identify surface and underground water bodies that are potentially radiologically impacted.
- Identify a preliminary list of radionuclides of concern needed to support the initial radiological characterisation, taking into account the following criteria:
  - radionuclides detected during operational surveys, in radiological effluents and in radioactive wastes.
  - bibliographic references and references to other similar nuclear installations.
  - radionuclides that will contribute in a non-negligible manner to potential doses from clearance practices or waste disposal, taking into account radioactive decay with respect to the date when these scenarios could occur.
  - preliminary identification and classification of the structures, components, systems and building areas into appropriate categories (e.g. no contamination/ contamination possible/contaminated).
- Estimate a preliminary radiological and physical inventory (activation and contamination included) and provide a support database to manage and store this information.
- Provide input data for designing future radiological characterisation campaigns (during the phases of transition, dismantling and final survey).

Radiological characterisation during the transition phase

The period between the permanent shutdown of the facility and the start of implementation of the decommissioning strategy is often called the transition phase. This phase normally contains activities that are covered by the operating license.

The transition phase is a critical period during which a number of modifications, both technical and organisational, are carried out. These modifications normally allow and require subsequent characterisation steps. The characterisation information developed during the operational phase is usually re-examined with respect to the assumptions made, the actual status of the facility after final shutdown, the accuracy of the measurements required and changes in facility radiological properties during the transition phase.

Depending on the requirements in a specific country, it may be the case that a new license/permit/authorisation for the transition phase must be applied for by the operator (if the operational license will not cover the transition phase). Then licensing documents must be adapted to the new risk profile. It will significantly facilitate implementation of the actions to be carried out during transition phase if a radiological characterisation programme and in particular access to all places where sampling and measurements are required is integrated in the license/permit/authorisation for the transition phase.

Characterisation during the transition phase is built upon historical site assessment data. The first step is to define a sampling and measurement plan based on the criteria and methodology established in the radiological characterisation programme. The main objectives of this characterisation are:

- Determination of the impacted areas, nature and extension of contamination and estimation of a radiological and physical inventory required for:
  - planning the dismantling activities;
  - planning the work from ALARA point of view;
  - effective planning for remediation (decontamination and restoration techniques) and waste disposal activities;
  - evaluation of management options for the residual materials;
  - assessment of the radiological impacts including effluents' releases for normal and accidental situations during decommissioning (both for the public and workers).
- Definition of input data required for management of radioactive waste and material eligible for clearance as well as of the final survey:
  - final list of radionuclides of concern needed to support clearance measurements, declaration of radioactive waste and the final survey;
  - definitive identification and classification of the structures, components, systems and building areas into categories (e.g. no contamination/contamination possible/contaminated);
  - estimation of the correlation factors between hard-to-measure radionuclides and key nuclides;
  - derivation of clearance levels or any derived concentration guideline levels (DCGL) in terms of Bq/g or Bq/cm^2 that are needed for performing measurements for clearance, license termination and site release;
  - selection of the appropriate measurement equipment that is capable of measuring the selected key nuclides with detection limits in accordance with the derived concentration limits.
- Planning additional sampling and measurements if required in order to define the parameters relevant for the final survey.

The result of the radiological characterisation during the transition phase is an important parameter for the design and the definition of the capacities of the auxiliary systems and facilities in preparation for dismantling, such as ventilation, filtration, radiation monitoring, radioactive waste treatment and conditioning, provisions for clearance measurements, etc. This also includes evaluation of suitable waste disposal containers with respect to volume and shielding requirements and their required numbers as well as estimation of space required in interim storage facilities and repositories.

Radiological characterisation during dismantling

The dismantling phase begins once the licence/permit/authorisation for dismantling has been obtained. This phase marks the performance phase of the decommissioning project as to when and how the decommissioning strategies and plans are implemented. It is a dynamic process that consists of a sequence of activities including, among others, more detailed characterisation and categorisation, dismantling, decontamination and other activities for materials management, re-characterisation, clearance and qualification of waste packages for disposal, demolition and restoration of the site.

An important consideration from a characterisation perspective is to detect, and if possible avoid, cases in which the application of decontamination and dismantling techniques could complicate, or partly nullify the relevance of previously performed characterisations, e.g. application of a specific technique for decontamination or dismantling:

- that might cause redistribution of contamination to previously decontaminated areas or areas with a totally different contamination profile;
- that would alter the nuclide composition significantly, rendering any previously determined nuclide vector useless.

This endeavour can be supported by including well-defined checkpoints into the clearance procedure at which the results from the radiological characterisation are consulted and checked, e.g. nuclide compositions, assignment to categories, etc.

The considerations listed in the previous section with respect to the transition phase also apply to varying extents during the dismantling phase, mainly those related to the parameters required for the final survey. In addition, after implementation of certain decontamination or restoration activities, new characterisation will be required, the main objectives of which are to:

- update the radiological inventory and the waste management plans;
- estimate the decontamination factor and the efficiency of the decontamination/ remediation process;
- update the final survey parameters (list of radionuclides to include, their specific activities and their distribution, correlation factors, etc.).

The documents required to obtain a license/permit/authorisation for decommissioning need to be adapted to the new risk profile; and the administrative process for design modifications, based on the results of characterisation, should be simplified so as to maintain fluid and transparent communication with the competent authorities.

Radiological characterisation for final survey

When physical dismantling, as well as decontamination and remedial actions have been completed, a final radiological survey will have to be conducted to demonstrate that the site of the nuclear facility and any remaining buildings can be released for restricted or unrestricted use.

The results of previous phases are the basis to plan the final survey. This survey provides data to demonstrate that all radiological parameters satisfy the established guideline values and conditions. In this regard, the following important considerations need to be addressed:

- demonstration that the technologies and methods applied are adequate to achieve the objective of site release and that uncertainties are defined in a transparent manner.

- issues pertaining to how to build confidence towards stakeholders to assure that all relevant actions are taken.

4. Key Activities in a Radiological Characterisation Campaign

This chapter describes key issues that are relevant for a radiological characterisation project during any phase of the life cycle of a nuclear facility, and for any type of material or object to be characterised. There are generic steps in any characterisation project, which are: initiation, planning, implementation, data assessment and decision.

Initiating step

Before starting a radiological characterisation, the requirements and targets of the data to support a planned activity need to be defined. The initiating step therefore consists of identification of the main objectives for the characterisation project. These should be clearly defined with respect to the definition of the part of the facility to which the work shall extend, the materials to be treated, the type of characterisation that is required, including provision of the reasons why the work is being carried out.

Planning step

There are different ways in which a characterisation project might be planned. One approach that is relatively common is to follow the principles of data quality objectives (DQO). This is a process for planning characterisation that was developed by the US EPA (2006) for use with contaminated land, but whose principles can provide structured planning for any characterisation project. The process comprises seven main steps:

- Step 1: State the problem.
- Step 2: Identify the goals of the study or the decommissioning project.
- Step 3: Identify information inputs.
- Step 4: Define the boundaries of the study.
- Step 5: Develop an analytical approach to address the problem.
- Step 6: Specify performance or acceptance criteria.
- Step 7: Develop the plan for obtaining data and results.

The DQO process is not linear, rather it is an iterative process during which it may become necessary to go back to previous steps as new data and information become available. Implementing systematic planning using the DQO methodology provides a logical framework for characterisation. By investing time and effort in the planning stages it can ensure that the end product satisfies all of the goals of the project and can provide clear justification for data collection, analysis and interpretation. The final section of Chapter 2, *Definition of clear objectives for radiological characterisation*, addresses the objectives of radiological characterisation. Key activities to consider further are:

- gathering of historical information;
- development of a sampling and measurement strategy;
- development of a sampling and measurement plan.

Historical information

An exercise to prepare a historical data document, whereby existing (historical) information about the site, the area or the facility under investigation and its operation is gathered and appropriately evaluated, is a recommended starting point. Maximising the use of existing analytical and historical information minimises the need for fresh sampling and analysis.

The purpose of compiling a history document is to collect, assess and comment on existing information. It is not the intent of this part of the characterisation process to create new information; however any obvious gaps in the available information can thus be identified and should be noted for further coverage.

The document should present a critical assessment of information, the quantity and quality of which can be variable for the intended use. This will reflect the degree of confidence that can be placed on the use of such information. Appendix A presents an example layout of a comprehensive history report. Overall, the objectives of the history report document may be summarised as given below:

- to describe the context (e.g. dates, location, activities, etc.) in which to consider the site of interest;
- to identify areas of concern (e.g. contamination, hazards, etc.) that would warrant further attention at later stages of the characterisation process;
- to highlight areas where there are gaps or inconsistencies in available information and where there are significant uncertainties regarding potential risks or hazards.

Based on the historical information, initial categorisations can be assigned to different parts of the area of interest, dependent upon the identified risk of radiological contamination. This will then assist identification of what information it is necessary to collect through characterisation.

By placing emphasis on the use of existing information the project can ensure that the characterisation that does take place will:

- provide sufficient data to make informed decisions within a reasonable uncertainty;
- collect only the amount of data needed to fulfil the objective of the characterisation project.

Strategy for sampling and measurements

The sampling and measurement strategy is set out to ensure that sufficient and appropriate data are collected to meet the defined objectives. It addresses the requirements that have been derived through the DQO process and then considers other significant factors such as:

- spatial and temporal constraints, e.g. physical constraints, high background radiation, the presence of hazardous conditions and resource/budgetary constraints as identified through assessment of relevant project information;
- other requirements relating to in-field sampling operations (notably labelling, containment, storage and dispatch) which require identification at the sample planning stage to assist in-field sampling resource during the execution of sampling operations.

In order to ensure that the sampling and measurement strategy is appropriate for the project needs, the objectives to be achieved by the sampling and measurement campaign should be reviewed prior to the actual execution of sampling and measurement operations.

Sampling design and analytic approach are closely linked to the evaluation objective. From this point of view, setting up an appropriate evaluation methodology is of prime importance.

In a very simplified, representation the main sampling and measurement methodologies are judgemental or probabilistic-based:

- Judgemental approaches can hold down sampling and measurement costs by focused sampling, but rely on good prior knowledge and the validity of their results is dependent upon the quality of judgement used. They are good for looking for worst cases, with a limited number of points rather than estimating means or testing hypotheses due to the obvious sampling bias.
- Probabilistic-based approaches (random or regular mesh) assume a random or spatial distribution hypothesis for which some historical information is necessary. Their mathematical structure allows inferences (using statistical or geostatistical data analysis) to be made from the samples to the whole population. Sampling optimisation (number of random points or size of the regular mesh) is therefore possible to meet the objective due to the uncertainty quantification.

In complex situations (e.g. where there is a high abundance of hard-to-detect radionuclides) a mixture of judgemental and probabilistic-based approaches may be necessary. Another case is the calibration of deterministic models (activation, ground water flow, atmospheric dispersion…).

More information on sampling and measurement strategies can be found in the appendices to this report:

- Appendix B lists detailed considerations when determining a sampling and measurement strategy.
- Appendix C lists considerations for in-field requirements during performance of sampling and measurement.

Sampling and measurement plan

A plan for performing sampling and measurement is needed for selecting and documenting the strategy chosen for sampling and performing measurements. Such a plan should consider:

- an introduction to the plant, the problem and the project aims/objectives;
- a summary of the sampling and measurement strategy, including both the result of the decision making from the strategy derivation and justification for that decision making;
- a summary of key health and safety issues derived from project information and discussion with the customer;
- a series of appendices detailing:
  - an analytical schedule (for distribution to the analysing laboratory);
  - a sampling schedule (detailing key in-field sampling parameters for use during execution of sampling operations).

The planning stage should also consider:

- any requirements for *in situ* measurements and how they will be achieved;
- the plan for analysis of measurement results and of samples;

- the means by which data from the characterisation work will be evaluated and stored afterwards;
- what validation will be necessary, e.g. of nuclide vectors (radiological fingerprints).

Implementation step

The implementation phase includes in-field measurements and/or sample collection and analysis, both of which are directed by the sampling plan.

Performing sampling and measurement

Sampling operations involve the collection of representative samples or the collection of appropriate representative non-destructive measurement (NDM) data, to provide material for analysis, subsequent data assessment and decision making.

The process for sampling and measurement operations consists of three main phases:

1) *Preparation*. Includes understanding of project sampling plan, production of necessary operational instructions, collection of sampling equipment and preparation of sample area. The preparation phase must comprise calibration and testing of equipment and may also include personnel training and even, for unique, complex jobs, the development and testing of techniques and equipment.
2) *Execution*. Includes sample collection, performance of *in situ* measurements, health physics and safety survey of sample container(s), transfer of sample to sample store, completion of sampling record, post-job review.
3) *Dispatch*. Includes dispatch of samples to relevant lab, sample tracking and sample returns, as well as sample custody.

It should be noted that not all of these process steps are undertaken for all projects; and that the formality of some process steps is dictated by the complexity of the project and the experience of the samplers.

Errors to guard against during sampling are:

- improper selection and use of sampling tools;
- improper or missed calibration;
- insufficient number of increments;
- incorrect sample mass;
- loss of analytes (e.g. volatiles);
- cross-contamination;
- wrong sampling locations.

For more details regarding potential errors in sampling and sample handling see, for example, MARLAP (2004).

Analysis

The laboratories where the analyses of the samples are carried out should fulfil certain minimum requirements on QA/QC and certification to guarantee the reliability of data. Ideally, they should be accredited to the appropriate quality standard (e.g. to ISO 17025:2005 or equivalent). At the least, they should operate to internal quality standards that are comparable to those of a recognised standard.

Additional analyses – notably duplicate analysis, method blanks and quality control samples – should be undertaken for individual projects. The data from these samples can be used to identify anomalies, trends or patterns of interest, measure key statistical parameters (e.g. variability) and to identify appropriate action. This trending evaluation will enable method performance to be measured to maintain or improve the laboratory service.

The necessity for non-radiological characterisation (e.g. hazardous waste) should also be noted. Many samples that have been taken for purposes of radiological characterisation can also be analysed for other chemical constituents.

Data assessment and evaluation step

Data assessment involves the review and assessment of the data generated by analysis or measurement in order to make a decision in line with the project objectives.

A preliminary assessment of analytical data should be undertaken in a timely fashion, ideally as soon as possible when the data is received from the laboratory and prior to data being transcribed into any data assessment tool. This increases the likelihood that sufficient material will still be retained by the laboratory for any necessary re-analysis.

The preliminary assessment is a check for completeness and usability. Such an assessment is usually performed to ensure that an adequate data set is available for future decision making. This reduces the likelihood that re-work or re-analysis is required at a later phase of the project, thus preventing cost over-runs and delays in the project.

Where a data set is identified as unusable or anomalous, the issue should be formally raised with the laboratory. This enables progress on resolving the issue with the project as well as providing information to enable trending and performance tracking of the individual analytical laboratory.

If data are deemed to be complete and usable following a preliminary assessment, then they are transcribed into an appropriate data assessment tool or into an appropriate data report.

Statistical techniques can be applied to data assessment and characterisation projects as appropriate. Such statistical techniques include for example significance testing, outlier tests and calculation of mean at an appropriate confidence level (e.g. 95%, based on DQO). Different statistical approaches are appropriate when there are different purposes for the data gathering. Specific guidance on the use of statistics for data assessment can be found in the bibliography.

Conventional statistical and geostatistical models can be applied to optimise the radiological characterisation by reducing the number of samples or measurements required to meet the data quality objectives (DQO).

An effective process for validation and verification should be in place, for checking and approval of data assessment, and of any data assessment tools (e.g. spreadsheets) that are developed including audits and QA/QC. The uncertainties associated with the data assessment (e.g. uncertainties due to modelling measurements) should be identified and evaluated if possible. The results should be analysed through comparison with other sources.

Personnel should undergo training and competency assessment as concerns data assessment activities. Assessment of competency should be proportionate to the complexity and significance of the data assessment tool.

Appendix B provides a table with considerations on how various objectives of data evaluation can be achieved through appropriate combinations of the sampling strategy and data analysis techniques.

Reporting

The outputs of the characterisation project should be drawn together into a final report that provides a translation of the data assessment into meaningful language for the user or customer with transparency for stakeholders' examination. It should assess the data against the characterisation goals and hence the initial problem statement. From these outcomes advice and judgment can be provided as described below:

- Advice is provided with regard to the improvement/support of the decommissioning strategy.
- It can be judged whether conditions are sufficiently described to evaluate the acceptability of the decommissioning plan.
- Waste routing is enabled by summarising the radiological and/or non-radiological content and classification and the justification for that classification.

The outputs should be clearly linked to the initial objectives so that future users understand its limitations.

It is good practice to undertake a post-project review, to evaluate the project against success criteria; to identify successes, failures and lessons learned during project planning, execution and reporting to enable continuous process improvement; and to identify and quantify (where appropriate) any business benefits realised from project execution.

The final task should be completion and auditing of the project record. This ensures consistency in the quality of the project output and records. The storage medium or record management system needs to be designed to maintain the data in a useable format for the time span across which it might be needed. This may mean a long-term plan for the transfer of records across different media.

5. Selection of Strategies and Management Aspects

This chapter deals with the selection of strategies for performing radiological characterisation, making use of the methodology described in Chapter 4 and distinguishing between the various phases addressed in Chapter 3.

Staff requirements for radiological characterisation

The compilation and evaluation of a large database of knowledge on the radiological status of a nuclear facility represents a significant amount of work. In addition, radiological characterisation is a task which needs to be carried out in a well-structured and coherent manner by a staff with appropriate competence. This means that it is desirable to allocate a sufficiently large number of staff to this task who have the skills and are experienced in:

- the plant history;
- radiochemical aspects;
- setting up sampling and measurement plans and associated data management;
- measurements (various techniques that are applied for different materials, different types of radioisotopes, etc.);
- collecting and interpreting measurement data in connection with the plant design and its operating history.

Experience has shown that this task can often not be performed by staff already charged with routine operations, although clearly they may add considerable value in informing judgement. In large facilities, radiological characterisation should rather be treated as a separate project or should be incorporated as a well-defined task within projects. In any case, radiological experts should be involved in planning and analysis of any characterisation activity and in the planning of any decommissioning activity.

Measurement and sampling aspects

The aspects listed in the following subsections should be taken into account when devising a measurement strategy for radiological characterisation. A more in-depth discussion can be found in Appendix H of MARSSIM (US EPA, 2000).

In situ versus laboratory measurements

There is some question as to whether measurements should rely more on sampling with subsequent laboratory analysis or *in situ* methods like:

- dose rate measurements;
- measurements with surface contamination monitors;
- measurements with *in situ* gamma spectrometry;

- swipe tests.

This should be evaluated for each facility individually. The strategy is influenced to a large extent by the type of contamination that is present, or by the robustness of historical information about the contamination:

- The presence of alpha and beta emitters that emit no or only weak gamma radiation requires the use of sampling and subsequent laboratory analysis, if necessary with radiochemical analysis.
- Very heterogenic contamination will also require the additional use of samples to analyse or verify the nuclide composition.
- Contamination that has penetrated into the matrix, like contamination of concrete structures that are not protected by an impermeable coating, will also require sampling (in particular core samples) to determine the depth profile and the penetration depth.
- Activation will also require samples to be taken from the volume to verify activation calculations that have been performed as part of the radiological characterisation.
- Other types of contamination, e.g. purely superficial contamination on metallic surfaces or on building surfaces with no or small penetration depth, can often be measured with *in situ* measurement techniques, if the surrounding radiation level does not disturb the measurement.

Use of proven techniques

A further question that needs to be decided early in the process of radiological characterisation is the type of measurement techniques to be applied. As pointed out in Chapter 4, a large number of measurement techniques are available that can cope with virtually all types of contamination and activation in all media. All techniques have pros and cons, often leading to a balance between measurement time on the one hand and sensitivity or inaccuracy on the other. There are several techniques available, like inductively coupled plasma mass spectrometry (ICP-MS), that provide a very rapid measurement method but can reach sufficiently low limits of detection only for heavy elements like U and transuranics.

The decision for a specific set of techniques needs to be based on careful weighing of the savings from faster and more efficient execution of measurements by using new and emerging techniques against the possible increased costs for putting these techniques into service.

Combination of various measurement techniques and statistical approaches

Measurements performed within the framework of radiological characterisation ahead of decommissioning do not have the same purpose as measurements performed during clearance procedures. Therefore, they do not have to cover the entire surface of metallic materials or building structures and do not need to reach very low detection limits, as would be necessary to verify the absence of contamination above clearance levels. This opens the opportunity of combining various measurement techniques, including statistical approaches, in an effective manner, e.g.:

- A measurement covering a large area, e.g. uncollimated *in situ* gamma spectrometry or dose rate measurement, can be used to determine the overall contamination level.
- Several localised measurements, e.g. with surface contamination detectors, with collimated *in situ* gamma spectrometry or by swipe or material samples, can be used to determine the local contamination levels and their variation. These

measurements can then be evaluated using simple statistical approaches, like determination of the mean and the variance.

This will allow determination of the average contamination level of a system, building surface or land area together with the associated uncertainty level and thus determine the necessity for decontamination. This approach has a high potential for reducing the overall decommissioning costs. Radiological characterisation carried out for the derivation of nuclide vectors can also be assessed with respect to the homogeneity of the contamination.

During radiological characterisation, statistical approaches can also be applied to determine the nuclide composition (nuclide vector/radiological fingerprint) on the basis of averaging the activity percentages for all relevant radionuclides over a set of samples.

Use of data management tools

There are a large number of data management tools available today that can be used for the following purposes during radiological characterisation:

- input and storage of all measurement and sampling data during radiological characterisation, including additional information about the exact location and date where and by whom the sample has been taken or the measurement has been carried out;
- quality assurance of the data (plausibility checks, approval procedure for data sets by senior staff, etc.);
- correction for radioactive decay of the radiological data to the current date;
- grouping of a set of data that belong to one entity that has a common background with respect to operational history and contamination, e.g. one engineered system, one room, one area of the site;
- statistical evaluation of a set of data with respect to characteristic features (mean value, variance, test of value set for belonging to a single statistical population, etc.);
- generation of nuclide vectors/radiological fingerprints according to predefined methods;
- archiving of data and generation of documentation.

Some of these tools combine the functions of database and data analysis with the ability to visualise the data on 2-D or 3-D models of the systems, rooms or site of the facility, thus allowing an easy appraisal of the progress of radiological characterisation and the coverage of the facility that has been achieved.

The use of suitable data management tools is indispensable, as the data has to be kept available for years or even decades, and the QA process must be transparent and traceable. This can hardly be achieved by using spreadsheets or paper-based solutions.

Use of integrated approaches to characterisation

When planning radiological characterisation for systems and structures within facilities, it is a good idea to devise the characterisation in such a way that it will also provide information for the subsequent characterisation of building surfaces. Likewise, when buildings are characterised, especially for leakages through the foundation and for contamination on the exterior, it may be possible to gain some insight into the contamination situation on the site.

In particular, synergy may be reached by the following approaches:

- Scaffolds that have been erected for taking samples from systems may also be used simultaneously for taking samples from adjoining building surfaces.
- Nuclide vectors for outer surfaces of systems and structures may be the same as for building surfaces in the same room, as the contamination mechanism may be identical. Samples and measurements may therefore be taken at the systems and structures as well as on building surfaces in order to establish the nuclide vector.
- The results of radiological characterisation may be entered into databases that will allow visual representation of the data. In this way, an overview can be obtained simultaneously for systems and structures as well as for building surfaces in the same room and inconsistencies of results can be easily detected.

Approaches like these will maximise the use of the information and data gathered from the facility and will help planning of the next step.

Organisational aspects

Radiological characterisation is a task that requires a dedicated project structure and staff that will have enough time and resources to carry out the tasks. Experience from decommissioning projects has shown that the task group dealing with radiological characterisation should be appropriately merged into the project organisation, with a sufficient degree of being able to act independently. It may be assigned to a separate department, for example radiation protection or waste management, as radiological characterisation is relevant for a wide range of activities in nuclear installations.

Depending on the resources of the plant operator's staff, radiological characterisation may be carried out by contractors or by the staff itself. However, as the necessity to perform additional sampling and measurements later in order to broaden the database will always remain, it is advisable that the staff be adequately trained to be able to perform such tasks.

Another important aspect is the use of external laboratories in addition to or instead of laboratory equipment owned by the operator. The following considerations apply:

- The use of operator-owned laboratories requires investment in the necessary equipment and procedures and in staff competent to carry out measurements in a laboratory at the nuclear installation. The laboratory must be maintained, independent of the number of measurements and samples to be analysed.
- The analysis of samples in external laboratories will result in costs that are proportional to the number of measurements with no basic amount.

The choice between these options can obviously be narrowed down to a cost-benefit analysis. However, other considerations like the need for urgent availability of services should be included as well.

Common issues causing schedule delays, often-encountered obstacles

Experience from many decommissioning projects shows that there can be various unexpected developments causing delays to radiological characterisation or an increase in the required effort:

- One of the most common issues is related to the radionuclides to be included in the characterisation. If for example in the nuclide vectors of a nuclear power plant the alpha contamination has been neglected or has only been characterised as total alpha activity, because initial samples pointed to a low alpha content, then extensive and costly repetition of sampling and measurement will be required if it turns out later that it would have been necessary to distinguish between various alpha-emitting nuclides (^{241}Am, several U, Pu and Cm isotopes). This could have been avoided if the completeness of the nuclide vector had been assessed in the beginning, e.g. with the help of burn-up calculations and alpha spectrometry.

- In systems of nuclear power plants the nuclide vector may often change at filters or places where phase transitions (steam-water, water-steam, etc.) or other viable concentration mechanisms occur. The sampling and measurement strategy for radiological characterisation should take this into account by placing a sufficiently large number of samples and measurements on either side of such points. Otherwise it may become necessary to repeat part of the sampling process to achieve a sufficiently large number of samples in each part of the system.
- The use of certain decontamination techniques may lead to changes in the nuclide vector, which may not have been taken into account in the planning of the radiological characterisation process. In particular chemical decontamination methods have the potential to selectively reduce the amount of certain elements (e.g. metals) while not or only slightly affecting e.g. actinides, thus altering the composition of residual contamination in percentage terms (in this example, the percentage of alpha emitters would increase). This would render any characterisation aiming at derivation of nuclide vectors *prior* to the application of the decontamination process useless and is one of the reasons why in many decommissioning projects mechanical decontamination techniques are applied which tend to affect all constituents of contamination layers rather equally.
- While the use of protective coating on metallic and building surfaces against contamination is effective for easy decontamination during the operational phase for radiation protection purposes, it is often found to be an obstacle for radiological characterisation. In many cases this coating has been refurbished by applying a new layer on top of existing ones without full decontamination of the lower layer, which is acceptable from the point of view of radiation protection for the personnel. Multiple layers will, however, render measurements useless that have been carried out on the topmost layer with contamination measurement devices, as such measurements do not detect activity in greater depths. In cases where multiple layers are discovered only afterwards, extensive re-investigation or reliance on samples will be needed. Similar considerations apply to building surfaces where the penetration depth has been incorrectly determined.
- Very mobile radionuclides like ^{3}H may cause problems concerning the correct determination of their penetration into metallic structures and in particular into building surfaces. This may be an issue when performing radiological characterisation with respect to compliance with clearance levels.
- The presence of radioactive waste may interfere with *in situ* measurements, as the dose rate caused by radioactive waste in neighbouring rooms may influence the count rate of the measurement device, leading to the false assumption of higher levels of contamination or activation being present or preventing the use of such *in situ* measurements altogether.
- The possibility of the presence of subsurface contamination below buildings or in the soil of the site should be clarified as early as possible in order to properly devise the sampling and measurement plan for buildings or the site. If subsurface contamination is discovered only after normal radiological characterisation on the surface has been completed, a large part of the work would need to be repeated to perform sampling to greater depth. Because of its singular nature, subsurface contamination is treated separately below.
- The equipment required for radiological characterisation needs to be identified early on in the project so that it can be requalified. The use of existing equipment

in the installation to perform radiological characterisation (e.g. robotic arm) can be problematic if the equipment is defective (e.g. impact on planning, loss of measurement devices).

Careful planning and, in particular, exchange of information with those working on similar decommissioning projects may help to avoid such failures and impediments.

Strategies for subsurface contamination

While contamination on metal surfaces can have penetrated into the material at the most a few mm at cracks or corrosion and contamination on building surfaces a few cm up to a few 10 cm and thus can be easily detected during the radiological characterisation, the situation is fundamentally different with certain types of contamination in soil. Contamination from leaking pipes in the ground, from spillages or from contaminated material that has been kept outdoors for a lengthy period may have penetrated into the ground to depths that are *a priori* unknown, leading to a subsurface contamination that is very hard to detect and for which the size, dimensions and radionuclide transport rates need to be determined through very complex sampling and measurement campaigns. If the contamination extends to areas underneath buildings that are not to be removed, then there is the additional complication of gaining access to the contaminated area and performing appropriate sampling/measurements.

Subsurface contamination therefore may constitute a problem that requires an approach totally different from those described above for metallic structures, buildings, other materials and soil near the surface, as the effort for obtaining samples and measurements at greater depths is extremely high and any residual contamination may affect environmental media such as ground water for a significant period of time. The characterisation effort itself may also have a negative impact on the radiological status of the affected media, like boreholes for monitoring wells that may lead to connections of aquifers that previously were separated, causing the spread of contamination to other ground water layers. Starting from these considerations, the strategies for addressing subsurface contamination can be established based on analysis of the following aspects:

- review of site historical data and operational records to identify spills, operational events, and/or releases that may have caused releases to the subsurface;
- review and assessment of environmental monitoring data to identify potential impact to the subsurface including subsurface soil, ground water, sediments and surface water;
- assessment of type and potential extent of subsurface contamination and concentration or radioactivity levels;
- collection of subsurface data, if necessary, to establish reasonable confidence in bounding subsurface contamination.

The radiological characterisation is relevant for carrying out the following tasks that are generally associated with subsurface contamination, albeit with differing levels of detail:

- assessment of potential risk to the environment and of doses to members of the public taking into consideration the decommissioning performance period and plausible exposure scenarios;
- comparison of potential risk/dose arising from subsurface contamination with dose/risk criteria for site release after finalisation of decommissioning as required by the regulatory authority;
- assessment of possible remedial actions if necessary and evaluation of cost;

- use of cost/risk analysis and the ALARA concept for optimisation to reduce potential impacts to the environment and the public.

Assuming the risk/dose associated with subsurface contamination is significant compared to release criteria, 3-D sampling and modelling may be necessary to evaluate contaminant plume and potential transport and subsequently focus on remediation of areas of high activity. It should also be noted that dose impact exposure scenarios may need to be developed and assessed based on *potential* impact from subsurface sources of contamination. In such a case, the sampling/measurement programme must demonstrate the absence of such contamination.

Under certain conditions, restricted site release based on specific land use may be accepted by regulatory authorities, particularly if the cost of subsurface remediation is prohibitive, in which case the radiological characterisation needs to inform the process of devising long-term monitoring strategies.

6. Lessons Learned

This chapter describes some lessons learned based on experience from numerous decommissioning projects, grouped according to the various phases of the life cycle.

During operation

- Operational strategy and company culture during operation has a large impact on the conditions for characterisation. Examples range from actions in case of fuel failures and spillages to management of observations and record keeping. An open company culture and good record keeping will provide good input for the plant history and starting points for a measurement strategy.
- When the date of final shutdown has been established, it is best practice to draft an entire decommissioning plan, which also needs to be supported by a plan for radiological characterisation.
- The culture among employees and managers during operation will have an influence on the quality of record keeping, health physics practice, documentation of events, etc. This indirectly will affect the characterisation cost. Short-term savings during the operational phase have to be judged versus total life cycle cost. Records from the operational phase showing any spills or releases, as well as records for any decontamination actions taken, need to be maintained.
- Facility changes may complicate characterisation efforts, especially if they are not well documented. An example that is found in many installations is covering contamination with new layers of paint or even new concrete layers on floors, previously common procedures that are now widely recognised as bad practice but which cannot be avoided in some instances.
- Monitoring programmes for surface and groundwater during operation help detect any leaks and thus enable preventing contamination that might require extensive remedial actions during decommissioning.
- Records of environmental monitoring particularly for subsurface, ground water and surface water need to be maintained. They form a valuable input for the radiological characterisation.
- Confidence building with stakeholders, in particular with local groups, will help maintain smooth progress into decommissioning and will foster credibility of radiological characterisation results.

During the transition phase

- Transfer of knowledge from operators to the decommissioning staff is crucial (walk downs with former personnel, historical site assessment, amending incomplete records of events during operation, etc.).
- Apart from the pure radiological characterisation, characterisation of other types of risks (conventional industrial risk, radiological protection) must not be neglected,

as such risks could be more relevant during dismantling than nuclear safety. During the transition phase and later during decommissioning, areas of the plant may have to be entered that were never entered during operation.

- Early assessment of potential sources for contamination on building surfaces, soil, ground water and surface water helps create a solid sampling strategy. Early identification of characterisation needs for the different areas or environmental media is important.
- Preliminary assessment of levels of risk/dose associated with sources of contamination and initial estimate of derived concentration levels (clearance levels, DCGLs) to meet regulatory criteria. In this context, dialogue with regulatory authorities and other stakeholders as early as possible is recommended.
- It is important to establish clear characterisation objectives appropriate to each characterisation campaign based on assessment of contamination levels and potential remedial actions to satisfy the planned end state. This has to take place in accordance with the decommissioning budget, which means that if necessary the end state has to be redefined so that it can be reached with the allocated funds.
- Selection of characterisation and survey tools/instruments and protocols should be compatible with the derived release criteria.
- Consultation with regulatory authorities and dialogue with stakeholders during development of the decommissioning plan and/or post-shutdown clean-up activities will help foster acceptance for the results of radiological characterisation and decisions based on it.
- Remaining radioactive waste can be a major obstacle for characterisation during the transition phase. It is advantageous to ship operational waste off-site as early as possible.
- The radiological characterisation carried out during the transition phase should cover all parts of the facility.

The licensing process

- Regulations on performing characterisation for decommissioning have been developed, but they are often kept less explicit than those for operation, due to the varying demands that decommissioning will pose. Therefore, dialogue and consultation with the regulatory authorities is important to avoid problems later in the decommissioning phase.
- If necessary, licensing documents for the transition phase and the decommissioning phase must be adapted to the new risk profile. The license/permit/authorisation governing the transition phase should include the preparatory activities for the dismantling and decommissioning project and the spent fuel storage, in particular with respect to radiological characterisation. A timely planning and performance of radiological characterisation for elaborating licensing documents is important.
- The administrative process for design modifications should be simplified to also allow early characterisation on parts that may not be accessed during operation (e.g. parts of the primary circuit in nuclear power plants). Conditions of the license/permit/authorisation should not unnecessarily obstruct radiological characterisation.

Material management

- Radiological characterisation before, during and after dismantling, as well as during and after remediation, is a key element for efficient material management. Lack of clearance regulations or of clear definitions of the clearance process leads to uncertainties regarding the detection limits that have to be achieved during radiological characterisation.
- Characterisation requirements that have a direct relation to the clearance process (such as development of nuclide vectors or radiological fingerprints) must be developed early. This will also influence selection of appropriate sampling and measurement techniques.
- The process for clearance of materials and buildings should have well-defined checkpoints where the results from the radiological characterisation are consulted.
- A physical and radiological inventory database with built-in quality assurance functions is very important to manage the physical and radiological information in an efficient way.
- The material management in principle involves the risk of internal contamination with radioactive material. A more extensive contamination monitoring programme for workplaces and of individuals than during operation may therefore be required, especially for alpha contamination.

Design of auxiliary systems and facilities

- The result of the radiological characterisation is an important parameter for the design of the auxiliary systems and facilities, such as ventilation and filtration systems, radiation monitoring systems and radioactive waste treatment and conditioning facilities, and for selecting their capacities according to the estimated risks and the identified radioactive wastes streams.

Human and organisational issues

- It is necessary for multidisciplinary groups to be involved and co-ordinated in development of the decommissioning plans, the characterisation objectives for each characterisation campaign, and in selecting survey/characterisation tools and methods throughout all phases of the decommissioning project.
- Radiological expertise should be involved at all stages of characterisation and decommissioning planning.

7. Areas Suitable for Further Examination

The following is a list of topics that may be suitable for further examination with respect to radiological characterisation:

- Performance of radiological characterisation in nuclear facilities where a major event has happened and where the contamination situation is thus significantly altered and where some areas may not be readily accessible. In such cases, remote measurement techniques and methods relying on modelling and calculation of possible activity distributions may become relevant, while direct measurements and sampling are often impeded or even impossible due to high dose rates and other hazards.
- Specific aspects of subsurface radiological characterisation. This is an important topic mainly for nuclear power plants and fuel cycle facilities where during a long operational period leakages have occurred and contamination has spread in environmental media. In such cases, the sampling and measurement strategy has to be optimised in order to gain maximum knowledge of the radiological situation from a limited amount of data.
- Optimisation of characterisation efforts in a plant life cycle perspective; a more in-depth analysis of the interdependence between data obtained in previous phases and use of these data in later phases, as presented schematically in Figure 3.1, would provide insight in areas where characterisation could be made significantly more effective. A strategic characterisation programme taking into account data requirements of later phases would reduce the overall effort of radiological characterisation.
- The development of non-standard and emerging techniques for sampling and for measurements and their future role in radiological characterisation. Such an analysis would help identification of areas in which the most promising new techniques emerge that would be capable of solving current problems (e.g. efficient determination of alpha activity and its composition, depth distribution of activity in building structures, etc.). For this analysis the forthcoming OECD/NEA WPDD *Report on R&D and Innovation Needs for Decommissioning* (2013) could provide significant help.
- The interdependence between the results of radiological characterisation and dose assessments for workers and environmental issues. In such an analysis, the role and use of specific results of the radiological characterisation can be discussed, e.g. appropriate methods for derivation of sufficiently conservative nuclide vectors from a set of measurements, the implication of the presence of alpha-emitting nuclides on radiation protection of workers or the derivation of clearance levels for radionuclide mixtures as determined from the radiological characterisation.

Performance of such activities would put radiological characterisation in perspective with regard to other aspects of decommissioning, radiation protection, waste management, etc., and help to better understand its role in the context of the life cycle of nuclear installations.

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US EPA (2006), Guidance on Systematic Planning Using the Data Quality Objectives Process, EPA QA/G-4, Office of Environmental Information, Washington, DC, accessed 11 September 2013, www.epa.gov/quality/qs-docs/g4-final.pdf.

Appendix A. Layout of Facility History Report

Section	Title	Purpose
Project definition		
1	Project description	– Defines the scope of the study. – Explains why the study is being carried out.
Location-specific factors		
2	Dates and description of site prior to construction of facility/facility containment	– Describes the history of the land on which the facility was built (e.g. any earlier buildings or structures).
3	Dates and description of facility construction/modification	– Defines when the facility was built, its size, its layout, building materials, excavation, etc. – Describes any major extensions/modifications/demolitions that have taken place.
4	Dates and descriptions of developments in vicinity of the facility	– Defines the buildings/structures/objects that are nearby and could have an impact on the facility in question.
5	Potential hazards arising from facility construction/modification and location	– Combines the information given in Sections 2 to 4 to identify the hazards resulting from facility in its particular location.
Usage-specific factors		
6	Responsibility and ownership	– Identifies which groups have owned the facility. – Identifies who currently is responsible for it. – Identifies what the facility is currently used for.
7	Dates and description of facility usage	– Defines the functions (with dates) of the facility. – Explains the activities and processes that have been carried out in/by the facility. – Describes the major pieces of equipment that have been used.
8	Potential hazards/contaminants arising from facility usage	– Combines the information given in Sections 6 and 7 to identify contaminants that could potentially have arisen from activities associated with the facility.
Incident-related factors		
9	Events/incidents (including spillages) affecting facility	– Lists incidents that have been reported to have taken place in, or near to, the facility.
10	Potential contaminants associated with events/incidents (including spillages)	– Uses the information in Section 9 to identify likely areas of contaminations in and around the facility.

Section	Title	Purpose
Other factors		
11	Anecdotal evidence of contamination	– Lists "word of mouth" events that led to contamination for which there is no documentary support. – Provides further details of an incident that has been listed in earlier sections (this will usually be incorporated into the earlier description rather than described here).
12	Visual evidence of contamination	– Describes visible areas of contamination that have not been reported in any documents.
13	Olfactory evidence of contamination	– Describes smells that would possibly indicate areas of contamination that have not been reported in any documents.
14	Potential hazards associated with anecdotal, visual and olfactory evidence	– Combines the information in Sections 11 to 13 to highlight areas of potential contamination.
15	Other concerns relating to the building	– Describes any concerns not covered elsewhere (e.g. asbestos, legionella, unidentified objects, etc.).
Identification of areas of concern		
16	Conclusions	– Combines the discussions in Sections 5, 8, 10, 14 and 15 to outline the areas of concern that would warrant further attention during later stages of the characterisation process.
17	Sources of information	– Lists the information viewed in writing the facility history document.

Appendix B. Decision Making for Sampling Strategy

Decision	Key inputs and considerations to decision making	Good practice
Sampling approach	– Health physics survey data – Material type	Best quantitative results are generally from intrusive sampling. Non-destructive approaches may be best or only option for high-risk and high-activity projects, but generally provide semi-quantitative (relative) results.
Sample type	– Objective/aim of project – Material type – Constraints (particularly access) – Health physics survey data – Analysis costs	Discrete, composite and multi-incremental sampling types can be employed dependent on project objective. Discrete sampling tends to be used in situations where: – access to the sampling area is constrained; – the item or waste is of small volume or area; – if known contaminant hotspots are being investigated. Composite samples tend to be collected where there are a large number of sub-populations to be sampled and analysed, to minimise analytical cost. Multi-incremental sampling is used where the project objective requires maximised coverage and to enable a better estimate of the mean concentration of contaminants at minimal analytical cost. This is particularly used for large area or volume facilities, items and wastes where analytical cost is high compared to sampling cost and expected waste cost. For example, multi-incremental sampling is typically used in building characterisation to determine waste classification.
Sample format	– Objective/aim of project – Material type – Constraints (particularly access) – Health physics survey data – Cost	Both probability-based (simple random, random systematic and random stratified) and judgemental (targeted) methods can be employed, dependent on objective of project and chosen analytic method. Targeted sampling is used predominantly for screening (especially for small-scale projects) to determine the nature of future investigation. Systematic and stratified sampling formats are used where a project requires knowing when and where contaminants are present. Random formats are suitable to perform statistical tests (to demonstrate compliance with radiological criteria) or calculations (population mean, proportion, etc.).

Decision	Key inputs and considerations to decision making	Good practice
Number and distribution of sample populations	– Objective/aim of project – Material type – Constraints (particularly access) – Health physics survey data – History/provenance – Analytical constraints – Treatment and disposal requirements and constraints – Ease of segregation – Size of area to be sampled	Sample populations are selected on a project-by-project basis with due consideration of project objective, building/item/waste size and the capability for segregation of the building/item/waste. Populations are selected such that the size is manageable for purposes of intrusive sampling and data analysis, whilst providing sufficient information to meet the project objective.
Number and distribution of samples	– Health physics survey data – Provenance/history of building/item/waste – Access constraints	Generally project information (principally health physics survey data, provenance/history, etc.) is used to determine an appropriate number and distribution of samples to be collected. Judgement is used to maximise coverage across given sample populations within project constraints. Triplicate samples tend to be collected for multi-incremental sampling in order to verify that the multi-incremental sample truly represents the sample population. Triplicate sampling allows for statistical manipulation of analytical data (e.g. the calculation of relative standard deviation). There may be specific guidance for determining the number of samples for specific circumstances. Otherwise, where any existing guidance is unavailable or inappropriate, experience and judgement is used to maximise the number and distribution of samples across a given population. The degree of randomness of sample distribution within a sample population, particularly where probability-based sample formats are applied, is important. Appropriate techniques should be chosen to ensure randomness in the choice of sampling location.
Analytical schedule	– Objective/aim of project – Waste acceptance criteria for treatment and disposal facilities – Provenance/history of building/item/waste – Material type – Analytical capability – Historical characterisation data – Facility fingerprint	The choice of analytical schedule is decided on a project-by-project basis based on review of project objective, projected project outcomes (i.e. material treatment and disposal routes) and project information.
Sampling technique	– Objective/aim of project – Material type – Health physics survey data – Access constraints – Sample size – Available equipment and competent resource – Sampling location/ environment	The selection of sampling technique is based on assessment of the material to be sampled, location of sampling and sampling objective.

Decision	Key inputs and considerations to decision making	Good practice
Analytical laboratory	– Conditions for acceptance for analysing laboratories – Local issues with laboratories (e.g. workload, capability, etc.) – Involvement in previous work related to project	The choice of analytical laboratory is guided by the technical capability of the laboratory (i.e. ability to undertake analysis, activity of sample and compliance against conditions for acceptance) and local issues (e.g. workload, method performance, etc.).
Sample size	– Objective/aim of project – Analytical laboratory requirements – Analytical schedule	The sample size should be that required to provide a representative sample of the item/waste/material being characterised. As a minimum, the sample size should be the minimum quantity of sample required to meet the analytical requirements for the project. Advice on sample size for specific analytical requirements is available from the analysing laboratories.
Sample depth	– Sample size – Objective/aim of project – Analytical schedule – Health physics survey data – Nature of building material/item/ waste – Provenance/history	Sample depth is decided on a project-by-project basis on review of the project information and objective of the study.
Sample record requirements	– Aim/objective of project – Nature of building material/item/waste – Provenance/history – Analytical requirements	As a standard, the sampling record records date of sampling, details of deviations from the sampling plan, quantity of sample collected, health physics survey information relating to the samples and identifies the sampler as well as pertinent photographs. Additional requirements for the sample record are decided on a project-by-project basis.

The following table provides considerations on how various objectives of data evaluation can be achieved by appropriate combinations of the sampling strategy and data analysis techniques.

Sampling strategy	*Combined with* ✚ Data analysis	*allow* = Evaluation objective	Additional comments
Unbiased (random or regular)	Statistics (correlation)	Calculation of nuclide vectors (fingerprints)	Few samples: direct ratios More data: correlation, PCA…
Unbiased (random or regular)	Statistics (hypothesis testing)	Deriving average concentration	Demonstrate compliance with regulatory or sanitary threshold Other statistical quantities available
Regular mesh (2-D)	Stochastic geometry	Identification of hot spots	Generally non-destructive Direct link between probability of hitting, mesh size and target size
Regular mesh (2-D)	Geostatistics	2-D mapping (contamination extent)	Generally non-destructive Based on spatial continuity analysis Easy re-sampling in uncertain areas
Regular and/or judgmental	Geostatistics	3-D mapping (waste categorisation)	Combined with historical information and 2-D mapping: sampling optimisation Contamination profile in depth
Judgmental	Deterministic model (activation…)	3-D mapping (waste categorisation)	Based on mathematical formulae Data required to calibrate model parameters

Appendix C. Decision Making for In-Field Sampling Requirements

The following table contains examples for key inputs to decision making and good practices that should be followed.

Decision	Key inputs and examples of decision making	Good practice
Sample labelling	– Nature of material [Asbestos survey, Material Safety Data Sheet (MSDS), Control of Substances Hazardous to Health (COSHH) assessment]	Samples are labelled with one pre-printed sample label detailing project reference number, sample number, date and specific comments. Labels are applied to the sample container bodies. Where the sample is known to possess additional hazardous properties (such as containing asbestos or posing chemotoxic hazards) additional labelling is employed to ensure plant, people and environmental safety during sample handling and storage. This consists of either the CHIP symbol in reference to the chemotoxic hazard or an asbestos label where the sample is known to contain asbestos.
Containment type	– Nature of material (Asbestos survey, MSDS, COSHH assessment) – Health physics survey data (expected activity of sample) – Analytical laboratory requirements	Sample containers must be suitable for the matrices being sampled and the analytes that are to be characterised.
Storage requirements	– Objective/aim of project – Nature of material (Asbestos survey, MSDS, COSHH assessment) – Health physics survey data (expected activity of sample) – Analytical laboratory requirements	The choice of storage location is directed by the activity of the sample. Special requirements for sample storage such as refrigeration (e.g. for soil samples) or segregation (owing to chemotoxic properties) or additional bonding (e.g. for liquid samples) are determined based on assessment of project information.

Glossary

Clearance level

A value, established by a regulatory body and expressed in terms of activity concentration and/or total activity, at or below which a source of radiation may be released from regulatory control.

Data Quality Objectives (DQO) process

Planning process when environmental data are used to select between two alternatives or derive an estimate of contamination. The DQO process is used to develop performance and acceptance criteria (or data quality objectives) that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions.

Derived concentration guideline limit/level (DCGL)

Value of the total activity or the mass or surface-related activity of radionuclides that has been derived on the basis of radiological considerations or radiological models, e.g. for purposes of releasing materials from radiological control (clearance).

Hard-to-measure radionuclides

Nuclides that cannot be easily measured through their gamma radiation or beta emissions; usually comprise alpha-emitting nuclides without strong beta or gamma lines or pure beta emitters. Examples are ^{3}H, ^{14}C, ^{36}Cl, ^{90}Sr, ^{99}Tc and ^{129}I.

***In situ* gamma spectrometry**

Gamma spectrometer together with computer and software that is designed to be operated in the field and not in the laboratory. Often used with collimator to suppress gamma radiation from directions other than the object to be measured.

Key nuclides

Nuclides that are easy to measure and have a high abundance in the nuclide mixture in question. The activities of hard-to-measure radionuclides may be correlated to the activities of key nuclides via scaling factors.

Nuclide vector

List of radionuclides present in the nuclide mixture (contamination, activation) together with its activity percentage. The activity percentages of all nuclides in the nuclide vector add up to 100%.

Scaling factors

Factor between a hard-to-measure nuclide and a key nuclide that represents the activity ratio.

Swipe tests

Extraction of a percentage of removable surface contamination by a pad or swab (wet or dry) in order to be measured by alpha, beta or gamma sensitive measurement methods in a laboratory. The removal factor is usually set conservatively low to the order of 10% of the total removable surface activity.

Transition phase

Period between the permanent shutdown of the facility and the start of implementation of decommissioning.

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1. *Radioactivity Measurements at Regulatory Release Levels*, OECD/NEA, Paris (2006).

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   The NEA Co-operative Programme for the Exchange of Scientific and Technical Information – Nuclear Installation Decommissioning Projects (CPD) is a joint undertaking of a limited number of organisations, mainly from NEA member countries. The objective of the CPD is to acquire and share information from operational experience in decommissioning nuclear installations that is useful for future projects. This report describes generic results obtained by the CPD on available, adequate methods for measuring radioactivity on materials to be released from regulatory control.

International Atomic Energy Agency (IAEA)

2. *Strategy and Methodology for Radioactive Waste Characterisation*, IAEA-TECDOC-1537, IAEA, Vienna (2007).

   www-pub.iaea.org/mtcd/publications/pdf/te_1537_web.pdf

   This international report covers:

   - requirements for and development of a waste characterisation;
   - programme strategy, quality assurance programme and quality control activities at the waste generator, processor, repository, and local or national laboratory levels;
   - characterisation responsibilities applicable to waste generators, processors and repository operators, as well as an examination of the cost and benefits of waste characterisation;
   - important factors to be considered in a waste characterisation programme, including accuracy and uncertainties, scaling factors and measurement methods.

3. *Innovative and Adaptive Technologies in Decommissioning of Nuclear Facilities: Final Report of a Co-ordinated Research Project 2004-2008*, IAEA-TECDOC-1602, IAEA, Vienna (2008).

   http://www-pub.iaea.org/MTCD/publications/PDF/te_1602_web.pdf

   Outcome of co-ordinated research project (2004-2008). There is a section on characterisation techniques.

4. *Site Characterization Techniques Used in Environmental Restoration Activities: Final Report of a Co-ordinated Research Project* 1995-1999, IAEA-TECDOC-1148, IAEA, Vienna (2000).

http://www-pub.iaea.org/MTCD/publications/PDF/te_1148_prn.pdf

Outcome of a co-ordinated research project reported in 2000.

5. *Radiological Characterisation of Shut Down Nuclear Reactors for Decommissioning Purposes*, Technical Reports Series No. 389, IAEA, Vienna (1998).

http://www-pub.iaea.org/MTCD/publications/PDF/TRS389_scr.pdf

This publication describes and assesses radiological characterisation as a precursor to decommissioning of nuclear reactors.

6. *The Decommissioning of WWER Type Nuclear Power Plants: Final Report of an IAEA Regional Technical Co-operation Project*, IAEA-TECDOC-1133, IAEA, Vienna (2000).

http://www-pub.iaea.org/MTCD/publications/PDF/te_1133_prn.pdf

This publication contains a short section on characterisation.

European Union

7. *Handbook on Measurement Methods and Strategies at Very Low Levels and Activities*, Report EUR 17624, European Commission, Nuclear Safety and the Environment (1998).

http://hps1.org/sections/decom/eur17624.pdf

Guidance on acceptable levels for the free release of materials is being developed within the European Community (EC) for general application for both surface and bulk activity. This handbook:

- reviews the capabilities and limitations of various types of monitoring equipment and practicable applicable methods, which can be used to demonstrate compliance with standards set for release of material;
- provides generic cost considerations;
- gives examples of the methods and instrumentation which have been employed and which look attractive for future work.

8. *RESTRAT: Restoration Strategies for Radioactively Contaminated Sites and their Close Surroundings*, EU Project FI4P-CT95-0021, in the framework of the Nuclear Fission Safety Programme (1999).

www.hzdr.de/projects/RESTRAT

9. *Environmental Radiation Survey and Site Execution Manual (EURSSEM)*, L. van Velzen, L. Teunckens, Eds., Co-ordination Network on Decommissioning of Nuclear Installations, European Community.

www.eurssem.eu/wiki

The Environmental Radiation Survey and Site Execution Manual (EURSSEM) provides information and guidance on strategy, planning, stakeholder involvement, conducting, evaluating and documenting radiological environmental and facility (surface) surveys based on best practices for demonstrating compliance with dose or risk-based regulations or standards, remediation, reuse, short-term and long-term stewardship on radioactively contaminated and potentially radioactively contaminated sites and/or ground water.

Germany

10. Thierfeldt, Stefan, "Decommissioning and Waste Management", *Third European IRPA Congress*, Radiation and Nuclear Safety Authority (STUK), on behalf of the Nordic Society for Radiation Protection (NSFS), Helsinki, Finland, 14-18 June 2010. Paper R15, p. 3033.

    www.irpa2010europe.com/pdfs/proceedings/R.pdf

    Good overview of decommissioning approaches and methods (including standard characterisation approaches).

Sweden

11. Meck, Robert A., *Approaches Used for Clearance of Lands from Nuclear Facilities Among Several Countries – Evaluation for Regulatory Input*, SSM 2013:14, Swedish Radiation Safety Authority (SSM), Sweden (2013).

    www.stralsakerhetsmyndigheten.se/Publikationer/Rapport/Stralskydd/2013/201314/

    The study evaluates methods and approaches used in different countries to achieve clearance of land where nuclear activities have been carried out (also called a site release). The different methods and approaches are analysed using a broad variety of attributes.

United Kingdom

12. "Radioactive Substance Regulations for the Environmental Permitting (England and Wales) Regulations 2010", Version 2.0, *Environmental Permitting Guidance*, Department for Environment, Food & Rural Affairs (DEFRA), London (2011).

    https://www.gov.uk/government/publications/radioactive-substance-regulations-rsr-guidance

    This guidance is aimed at helping readers understand the permitting and other requirements specific to Radioactive Substances Regulation (RSR). The RSR regime covers:

    - more than one European Directive, parts of which are also implemented by other regulatory regimes which, to an extent, complement RSR;
    - various government policies and strategies;
    - some duties delivered by other statutory requirements, such as trans-frontier shipments, and justification. Although not delivered by the Environment Permitting Regulations, these are briefly covered in this guidance for completeness.

13. Low Level Waste Repository (LLWR) Characterisation Guide, LLW Repository Ltd (n.d.).

    www.llwrsite.com

    Document available upon request.

14. Tattam, D., Keightley, L., "Radiometric Non-destructive Assay", *Measurement Good Practice Guide No. 34*, October 2012, National Physical Laboratory, UK (2012).

    www.npl.co.uk/publications/radiometric-non-destructive-assay.

    This guide from the UK national physical laboratory (NPL), published in 2012, provides recommended procedures for the operation, testing and calibration of equipment used for radiometric non-destructive assay of fissile and radioactive materials in the nuclear industry. The various techniques and their limitations are described. Guidance is given on calibration of NDA systems and the treatment of uncertainties in NDA measurements. Recommendations are made for certification, performance demonstration and testing; competence and responsibility; documentation and the control of modification.

15. Dean, J.C.J., S.M. Jerome, *A Survey of User Requirements for a UK Radioactivity Measurement Infrastructure for Nuclear Decommissioning*, NPL Report DQL RN 009, National Physical Laboratory, UK (2005).

    http://publications.npl.co.uk/npl_web/pdf/dql_rn9.pdf

16. The Management of Higher Activity Radioactive Waste on Nuclear Licensed Sites, Joint Guidance from the Health and Safety Executive, the Environment Agency and the Scottish Environment Protection Agency to Nuclear Licensee, Office for Nuclear Regulation, Health and Safety Executive, UK (2010).

    www.hse.gov.uk/nuclear/wastemanage.htm

    Part 3a: Waste minimisation, characterisation and segregation (February 2010) is also found at this location. This document provides an overview of the relevant policy drivers, regulatory requirements and expectations relating to waste minimisation, characterisation and segregation during the management of higher activity radioactive waste on UK nuclear licensed sites.

17. Environment Agencies Requirements Working Group, Re-Use and Recycling web page, EARWG (2013), accessed 15 September 2013.

    www.rwbestpractice.co.uk/ReUseAndRecycling.aspx

    Deals with nuclear industry best practice.

18. Safegrounds + Incorporating SD:SPUR: A CIRIA Learning Network, website managed by CIRIA (n.d.).

    www.safegrounds.org/index.html

    Consolidation of best practice guidance to meet Environment Agency requirements for authorisation. Includes information formerly housed across separate sites, namely SAFEGROUNDS, SD:SPUR and SAFESPUR.

    The initiative was developed to establish through dialogue safe, socially, economically and environmentally sustainable practices in the use of resources arising from the decommissioning of nuclear sites. Contains guidance on characterisation.

United States of America

Environmental Protection Agency (EPA)

19. Storms, R., S. Walker, "Interstate Technology Regulatory Council – Decontamination and Decommissioning of Radiologically-Contaminated Facilities Guidance", *WM2009 Conference*, Phoenix, AZ, 1-5 March (2009).

    www.wmsym.org/archives/2009/pdfs/9118.pdf

    Technical and regulatory guidance.

20. *Technology Reference Guide for Radiologically Contaminated Surfaces*, EPA-402-R-06-003, March (2006).

    www.epa.gov/radiation/docs/cleanup/402-r-06-003.pdf

    Technology Reference Guide for Radioactively Contaminated Media, EPA-402-R-07-004, October (2007).

    www.epa.gov/radiation/docs/cleanup/media.pdf

    These guides assist decision makers in identifying technologies that are potentially useful in removing radiological contaminants from building, structure and equipment surfaces as part of a site remediation and choosing technologies for treating land, groundwater and effluents. The guides are meant to be an aid to decision making and are not meant to replace other procedures that are acknowledged as critical to the decision-making process. It may be appropriate to gather information to support remedy selection and implementation through a small-scale engineering study. Such small-scale engineering studies are often laboratory-based tests that provide critical information on how a proposed technology will perform under particular real-world conditions. They are relatively low cost and are often used to provide better data support, remedy selection and valuation. Small-scale laboratory tests may be followed up with advanced or pilot scale tests if more remedy design information is needed.

    When properly designed a study should yield information on seven remedy selection criteria:

    - overall protection of human health and the environment;
    - compliance with clean-up levels;
    - long-term effectiveness;
    - reduction of toxicity, mobility and volume;
    - short-term effectiveness;
    - feasibility;
    - cost.

    Adequate characterisation of the surfaces, land or aqueous waste to be remediated before/after) will be important to the success of the studies. Recognition of the value of this approach will allow decision makers to budget early in the planning process for decontamination treatability studies, screen for potentially applicable decontamination technologies, develop remedial alternatives incorporating other considerations such as protective clean-up levels and waste disposal options, and perform a comparative analysis of alternatives to ultimately select the final remedial action technology.

21. *Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)* (2000).

    www.epa.gov/rpdweb00/marssim/

    The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) is a technical document for providing radiological survey approaches to United States federal agencies, states, site owners, contractors, and other private entities on how to demonstrate that their site is in compliance with a radiation dose or risk-based regulation, otherwise known as a release criterion. The MARSSIM radiological survey approach is the industry standard for radiological surveys in the United States. The MARSSIM approach is applicable to "real property" as defined in US legal practice. "Real property" consists of land, buildings and other permanent improvements fixed to the land (walls, utility piping, sidewalks and roads).

22. *Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual (MARSAME)* (2009).

www.epa.gov/rpdweb00/marssim/marsame.html

MARSAME is a companion document to MARSSIM released in 2009. MARSAME provides technical information describing a framework for planning, implementing and assessing radiological surveys of materials and equipment (M&E). MARSAME is useful in addressing the radiological survey needs of "personal property," as defined in US legal practice. Personal property includes materials, equipment, waste in containers, building debris and privately owned property (clothing, briefcases, purses, private automobiles and jewellery).

23. *Multi-Agency Radiation Laboratory Analytical Protocols (MARLAP) Manual* (2004).

www.epa.gov/rpdweb00/marlap/manual.html

The MARLAP Manual addresses the need for a nationally consistent approach to producing radioanalytical laboratory data that meet a project's or programme's data requirements. MARLAP provides guidance for the planning, implementation and assessment phases of those projects that require laboratory analysis of radionuclides.

24. *Guidance on Systematic Planning Using the Data Quality Objectives Process*, EPA/240/B-06/001 (2006).

www.epa.gov/quality/qs-docs/g4-final.pdf

The EPA has developed the Data Quality Objectives (DQO) process as the agency's recommended planning process when environmental data are used to select between two alternatives or derive an estimate of contamination. The DQO process is used to develop performance and acceptance criteria (or data quality objectives) that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions.

Department of Energy (DOE) guidance and technical information

25. Methods & Practices Handbook, Office of Environmental Management (n.d.).

http://energy.gov/em/methods-practices-handbook

This site provides useful information on various techniques for the decommissioning of nuclear facilities.

26. Deactivation & Decommissioning, Office of Environmental Management (n.d.).

www.energy.gov/em/services/site-facility-restoration/deactivation-decommissioning-dd

This site provides useful information on the decommissioning of nuclear facilities.

27. Deactivation and Decommissioning Knowledge Management Tool

https://www.dndkm.org/

The Deactivation and Decommissioning Knowledge Management Tool (D&D KM-IT) serves as a centralised repository providing a common interface for all D&D related activities. It assists users in gathering, analysing, storing and sharing knowledge and information within the D&D community. This approach assists in reducing the need rediscover the knowledge of the past while capturing the new knowledge and experience gained during D&D operations. Mainly US contributions, but includes limited information from the UK.

28. RESRAD Home Page, Environmental Assessment Division, Argonne National Laboratory (n.d.).

http://web.ead.anl.gov/resrad/home2/

The "RESidual RADioactivity" (RESRAD) computer codes calculate clearance levels for property using user inputs for the likely future use of the property. The codes are written and supported by Argonne National Laboratory. Numerous publications are available at the RESRAD web site, including the *User's Manual for RESRAD Version* 6, ANL/EAD-4, July 2001. The computer codes can be freely downloaded from the referenced web site.

29. Visual Sampling Plan (VSP), Pacific Northwest National Laboratory (n.d.).

http://vsp.pnl.gov/index.stm

VSP is a software tool that supports the development of a defensible sampling plan based on statistical sampling theory and the statistical analysis of sample results to support confident decision making. VSP couples site, building and sample location visualisation capabilities with optimal sampling design and statistical analysis strategies. VSP was developed at the Pacific Northwest National Laboratory in Richland, Washington.

Nuclear Regulatory Commission (NRC) guidance

30. *Consolidated Decommissioning Guidance: Characterization, Survey, and Determination of Radiological Critera*, NUREG-1757, Volume 2, Revision 1 (2006).

www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1757/v2/

This publication provides useful information on characterisation, survey and determination of radiological criteria and provides guidance on compliance with the radiological criteria for license termination.

31. Decommissioning Guidance, NRC webpage (n.d.).

www.nrc.gov/about-nrc/regulatory/decommissioning/reg-guides-comm/guidance.html

This web page provides links to a number of NRC documents and guides related to the decommissioning of a wide range of nuclear facilities.

32. *A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys – Interim Draft Report for Comment and Use*, NUREG-1505, Revision 1 (1998).

www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1505/

This report describes a nonparametric statistical methodology for the design and analysis of final status decommissioning surveys in support of the final rulemaking on Radiological Criteria for License Termination published by the NRC on 21 July 1997. The techniques described are expected to be applicable to a broad range of circumstances, but do not preclude the use of alternative methods as particular situations may warrant. The tests described are the Sign test, the Wilcoxon Rank Sum test and a Quantile test. These tests are performed in conjunction with an Elevated Measurement Comparison to provide confidence that the radiological criteria specified for license termination are met. The Data Quality Objectives process is used for the planning of final site surveys. This includes methods for determining the number of samples needed to obtain statistically valid comparisons with decommissioning criteria and the methods for conducting the statistical tests with the resulting sample data.

33. *Radiological Assessments for Clearance of Materials from Nuclear Facilities*, NUREG-1640 (2003).

www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1640/

This report provides detailed radiation dose calculations for the clearance of a wide range of materials.

34. *Minimum Detectable Concentrations with Typical Radiation Survey Instruments for Various Contaminants and Field Concentrations*, NUREG-1507 (1988).

www.orau.gov/ddsc/instrument/NUREG-1507.pdf

This report reviews numerous radiation detection techniques and instruments and estimates their sensitivity and detection limits.

35. *Low-Level Radioactive Waste Classification, Characterization, and Assessment: Waste Streams and Neutron-Activated Metals*, NUREG/CR-6567 (2000).

www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6567/cr6567.pdf

Very useful discussion of scaling factors and consideration of novel radionuclides.

36. ADAMS Public Documents, NRC webpage (n.d.).

www.nrc.gov/reading-rm/adams.html

Big Rock Point (Rev. 0), Haddam Neck Plant (Rev. 4), Rancho Seco (Rev. 0), Main Yankee (Rev.4) and Yankee Rowe (Rev. 1) License Termination Plans. These plans are lengthy documents and can be downloaded from the above-referenced website.

Non-governmental technical information documents

37. Abelquist, E, *Decommissioning Health Physics: A Handbook for MARSSIM Users* (2001).

Abelquist's work is a detailed technical guide for conducting MARSSIM surveys in the decommissioning of nuclear facilities.

38. Electric Power Research Institute (EPRI), *Decommissioning and Technology Development: Program Overview*, 2010 Portfolio (2010).

http://mydocs.epri.com/docs/Portfolio/PDF/2010_P041.09.02.pdf

See general introduction to their current work scope for decommissioning.

List of key EPRI documents and abstracts

39. *Groundwater and Soil Remediation Guidelines for Nuclear Power Plants*, Product ID 1021104 (2010).

The EPRI Groundwater and Soil Remediation Guidelines provide the nuclear power industry with technical guidance for evaluating the need for and timing of remediation of soil and/or ground water contamination from onsite leaks, spills or inadvertent releases to: a) prevent migration of licensed material off-site; b) minimise decommissioning impacts.

40. *Use of In-Situ Gamma Spectroscopy During Nuclear Power Plant Decommissioning*, Product ID 1021108 (2010).

Due to leakage and other events that may occur during nuclear power plant operations, soil, concrete and bedrock have the potential to become contaminated, and therefore must be characterised to demonstrate that they meet strict regulatory site release limits. This report provides detailed information on the use of portable gamma

spectroscopy systems for the characterisation and Final Status Survey of soil, concrete and bedrock contaminated with radionuclides at a number of plants undergoing decommissioning.

41. *Characterization and Dose Modelling of Soil, Sediment and Bedrock During Nuclear Power Plant Decommissioning*, Product ID 1019228 (2009).

    A decommissioning nuclear power plant must confirm that the radionuclides present in the soils, sediments and bedrock left on site at the time of license termination will meet the appropriate dose limits for site release. This process involves the characterisation, dose modelling, and if required, remediation, of these media. At some decommissioning nuclear power plants, the management of contaminated soil, sediments and bedrocks was a major project that led to generation of remediation projects and radioactive waste. This report documents the experiences, lessons learned, good practices and technologies involved in the management of radiologically impacted soils, sediments and bedrock at decommissioning nuclear power plants.

42. *Concrete Characterization and Dose Modelling During Plant Decommissioning: Detailed Experience 1993-2007*, Product ID 10155012 (2008).

    Several US nuclear power plants entered decommissioning in the 1990s. The cost effective characterisation of contaminated concrete remains a challenge for plants currently undergoing decommissioning. This report provides detailed information on projects involving the characterisation, dose modelling, remediation and disposal of contaminated concrete at a number of plants undergoing decommissioning.

43. *Final Status Survey and Site Release Experience Report: Detailed Experiences 1996-2007*, Product ID 1015500 (2008).

    Several US nuclear power plants entered decommissioning in the 1990s. The ultimate goal of the decommissioning of a reactor site (unless otherwise delayed due to a decision to place the plant in a SAFSTOR mode to be decommissioned at a later date) is to release the site for future use. This report provides detailed information concerning the preparation of release criteria a utility must meet prior to the release of the site, and the experiences obtained in performing the Final Status Surveys which demonstrate the site meets that release criteria. This report draws on the experiences gained at a number of sites that have achieved release of the site from the NRC license, and from other sites in the final stage of obtaining that release.

44. *Interim Report on Cumulative Risk Assessment for Radiological and Chemical Constituents of Concern at Decommissioning Sites*, Product ID 1011735 (2005).

    Decommissioning nuclear facilities focus extensive efforts on site characterisation to demonstrate regulatory compliance in the termination of site licenses. Many decommissioning sites, while recognising radiological characterisation and assessment needs, lacked experience in chemical risk assessment. This report documents plant approaches for performing cumulative risk assessments of both radiological and non-radiological constituents of concern.

45. *Capturing Historical Knowledge for Decommissioning of Nuclear Power Plants: Summary of Historical Site Assessments at Eight Decommissioning Plants*, Product ID 1009410 (2004).

    This report describes approaches utilised and experience gained in the development of early characterisation activities by a number of nuclear power plants undergoing decommissioning. In particular, the report provides experience and lessons of performing the Historical Site Assessment (HSA).

46. *Guide to Assessing Radiological Elements for License Termination of Nuclear Power Plants*, Product ID 1003196 (2002).

This report provides guidance in the preparation of a License Termination Plan (LTP) to utilities engaged in nuclear plant decommissioning. The US Nuclear Regulatory Commission (NRC) requires utilities to submit the LTP document years prior to the site license termination. This report focuses on the radiological components of the LTP. It identifies and addresses the regulatory requirements of each element in a way useful to the utility end user.

47. *Trojan Nuclear Plant License Termination Plan Development Project*, Product ID 1003423 (2002).

This report provides a concise account of the development of the first License Termination Plan in the nuclear industry to receive Nuclear Regulatory Commission (NRC) approval. The report includes details of significant challenges encountered during preparation and NRC review of the License Termination Plan, and discussion of how the utility addressed these challenges.

48. *Determining Background Radiation Levels in Support of Decommissioning Nuclear Power Plants*, Product ID 1003030 (2001).

This report is a technical reference for determining background radiation levels in support of surveys for decommissioning nuclear power facilities. Careful planning and data evaluation are essential for a valid survey. The report discusses important considerations for successful establishment of background levels for soils, surfaces, structures and ground water. It also explores alternatives to performing a formal background study.

49. *A Mobile High Resolution Gamma Ray Spectrometry System for Radiological Surveys*, Product ID TR-109035 (1998).

Surveying nuclear power plant sites for radioactive contamination is an expensive part of the overall decommissioning process. This report details a mobile radiological survey system designed to produce a rapid and cost effective radiological characterisation of outdoor land areas. The system combines high resolution gamma ray spectrometry with modern automated surveying techniques to precisely locate areas of contamination.

50. *Fort St. Vrain Decommissioning: Final Site Radiation Survey: Summary Report and Lessons Learned*, Product ID TR-107979 (1998).

This report describes the final step in the decommissioning process at Public Service Company of Colorado's (PSCo) Fort St. Vrain nuclear power plant. The final site radiation survey documents that all nuclear facility surfaces meet the established release limits for unrestricted use. The survey formed the legal basis for the termination of the Fort St. Vrain nuclear license, which occurred in August 1997. The lessons learned in this process will be valuable to other utilities with permanently shutdown plants.

Interstate Technology & Regulatory Council (ITRC)

51. *Decontamination and Decommissioning of Radiologically Contaminated Facilities*, Technical/Regulatory Guidance (2008).

www.itrcweb.org/Documents/RAD5.pdf

This document provides an overview of regulatory, technical and stakeholder aspects for the decommissioning of nuclear facilities.

52. *Triad Implementation Guide*, Overview Document (2007).

www.itrcweb.org/Documents/SCM-3.pdf

Triad is a best management practice developed from experience in the environmental field to provide the tools for making better clean-up decisions at contamination sites. The Triad approach is built on an accurate conceptual site model (CSM) that supports project decisions about exposure to contaminants, site clean-up and reuse, and long-term monitoring. The Triad approach also incorporates application of successful work strategies and the use of technology options that can lower project costs while ensuring that the desired levels of environmental protection are achieved.

Standards

53. International Organization for Standardization (ISO), *Scaling Factor Method to Determine the Radioactivity of Low-and Intermediate-level Radioactive Waste Packages Generated at Nuclear Power Plants*, Nuclear Energy – Nuclear Fuel Technology, ISO 21238:2007 (2007).

54. ISO, *Evaluation of Surface Contamination – Part 1: Beta Emitters (Maximum Beta Energy Greater than 0.15 MeV) and Alpha Emitters*, First Edition, ISO 7503-1:1988 (1988).

55. American National Standards Institute (ANSI), *Performance and Documentation of Radiological Surveys*, ANSI N13.49 (2001).

56. ANSI, *Characterization in Support of Decommissioning Using the Data Quality Objectives Process*, ANSI N13.59 (2008).

57. Zull, L.M., L.E. Boing, R.H. Meservey, "A New Approach to Development of Voluntary Decommissioning Standards", *Decommissioning, Decontamination, and Reutilization Technology Expo*, INL/CON-07-12248 (2007).

www.inl.gov/technicalpublications/Documents/3792211.pdf

58. ASTM International, *Standard Guide for Preparing Characterization Plans for Decommissioning Nuclear Facilities*, ASTM E1892 – 09(2009).

www.astm.org/Standards/E1892.htm

This standard guide applies to developing nuclear facility characterisation plans to define the type, magnitude, location and extent of radiological and chemical contamination within the facility to allow decommissioning planning. This guide amplifies guidance regarding facility characterisation indicated in ASTM Standard E 1281 on Nuclear Facility Decommissioning Plans. This guide does not address the methodology necessary to release a facility or site for unconditional use. This guide specifically addresses:

- the data quality objective for characterisation as an initial step in decommissioning planning;
- sampling methods;
- the logic involved (statistical design) to ensure adequate characterisation for decommissioning purposes;
- essential documentation of the characterisation information.

59. ASTM International, *Standard Guide for Selection and Use of Portable Radiological Survey Instruments for Performing In Situ Radiological Assessments to Support Unrestricted Release from Further Regulatory Controls*, ASTM E1893 – 08a (1997).

www.astm.org/Standards/E1893.htm

This standard provides recommendations on the selection and use of portable instrumentation that is responsive to levels of radiation that are close to natural background. These instruments are employed to detect the presence of residual radioactivity that is at, or below, the criteria for release from further regulatory control. Covers choice of instruments, their operating characteristics and the protocols by which they are calibrated and used to ensure that measurements meet the requirements for release from regulatory control.

Supply chain

60. DecomIT

www.decomit.com

DecomIT is an integrated decommissioning and waste tracking solution that provides full traceability from source to final disposal.

61. Brenk (Germany)

www.brenk.com/system/main.htm

Case studies

62. Chernobyl

Milchikov, A., M. Davidko, B. Poralo, *A Radiological Survey Approach to Use Prior to Decommissioning: Results from a Technology Scanning and Assessment Project Focused on the Chornobyl NPP*, Information Bridge website, US Department of Energy, Office of Scientific and Technical Information (1999).

www.osti.gov/bridge/purl.cover.jsp;jsessionid=0A80F079AF0D7CC36A56CF20699BA41E?purl=/13873-t8movs/webviewable/

63. Barnwell nuclear fuel plant

McNeil, J., "The Decommissioning of the Barnwell Nuclear Fuel Plant", *WM'00 Conference*, Tuscon, AZ, 27 February-2 March (2000).

www.wmsym.org/archives/2000/pdf/11/11-14.pdf

64. Research reactors in the United States

CH2MHILL, *Research Reactor Decommissioning*, Brochure (n.d.).

www.ch2m.com/corporate/markets/nuclear/assets/ProjectPortfolio/Nuclear_Research_Reactors_project_description_rev6.pdf

65. D3 research reactor in Denmark

Søgaard-Hansen, J. P. Hedemann Jensen, "Radiation Protection Issues Related to the Decommissioning of the DR3 Research Reactor", Third European IRPA Congress, Helsinki, Finland, 14-18 June (2010), p. 992.

www.irpa2010europe.com/pdfs/proceedings/S05-P05.pdf

66. Fuel identification in reactor fuel storage basin decommissioning (F reactor Hanford)

Smith, D.S., *et al*., “Fuel Identification in Reactor Fuel Storage Basin Decommissioning”, *International Containment & Remediation Technology Conference and Exhibition*, Orlando, FL, 10-13 June (2001).

www.containment.fsu.edu/cd/content/pdf/048.pdf

67. Barsebäck NPP, Sweden

Lorentz, H., “Barsebäck NPP in Sweden – Decommissioning Project, *WM2009 Conference*, Phoenix, AZ, 1-5 March (2009).

www.wmsym.org/archives/2009/pdfs/9350.pdf

Lorentz, H., “Barsebäck NPP in Sweden – Transition to Decommissioning; Socio-Economic Aspects of Decommissioning; What Did We Achieve During the Transition 1997-2008?”, *WM2009 Conference*, Phoenix, AZ, 1-5 March (2009).

www.wmsym.org/archives/2009/pdfs/9092.pdf

68. East Tennessee Technology Park

Roberts, S.J., *et al*., “Independent Verification of Non-destructive Assay Characterization Results at the East Tennessee Technology Park K-25 Building and Lessons Learned”, *WM2009 Conference*, Phoenix, AZ, 1-5 March (2009).

www.wmsym.org/archives/2009/pdfs/9271.pdf