Radioactive Waste Management
2017

Radiological Characterisation from a Waste and Materials End-State Perspective

Practices and Experience

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Radioactive Waste Management

Radiological Characterisation from a Waste and Materials End-State Perspective: Practices and Experience

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Cover photos: Building release measurements at the Würgassen NPP, Germany (PreussenElektra); Measuring contamination at Ranstad, Sweden (Studsvik).

Foreword

Radiological characterisation plays an important role in the decommissioning of nuclear facilities and is central to the planning, implementation and optimisation of decommissioning projects. Effective characterisation allows the extent and nature of contamination to be determined, thereby providing crucial information to support facility dismantling; the management of material and waste arisings; the protection of workers, the public and the environment; and associated cost estimations.

Recognising the important role and significance of characterisation throughout all phases of nuclear decommissioning projects, the Nuclear Energy Agency Working Party on Decommissioning and Dismantling (WPDD) established an expert group in 2011 – the Task Group on Radiological Characterisation and Decommissioning (TGRCD). In the first phase of its work, the group prepared a report entitled "Radiological Characterisation for Decommissioning of Nuclear Installations" (NEA, 2013), which provides strategic guidance for decision makers on the selection and tailoring of strategies for radiological characterisation and gives an overview of good practices for radiological characterisation at different phases of the life cycle of nuclear facilities.

The second (and most recent) phase of work of this group started in 2014, focusing on important material and waste end-state aspects to be taken into consideration while conducting characterisation. An international survey was conducted among a broad range of international experts to gather practical experience and to collect different specialists' views on good practice in radiological characterisation of materials and waste. A previously released intermediary report, entitled "Radiological Characterisation from a Material and Waste End-State Perspective: Evaluation of the Questionnaire by the NEA Task Group on Radiological Characterisation and Decommissioning" (NEA, 2016) summarises the survey.

The present report has been prepared from this survey evaluation, and it explores the practical implementation of nuclear facility characterisation from a waste and materials end-state perspective. The objective is to identify international good practices and to provide practical advice distilled from a questionnaire and international conference discussions on this subject, from case studies, and from international standards and guidance. This report is aimed at characterisation practitioners, with the information presented through a systematic discussion of the characterisation process.

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Chapter 1. Introduction

Radiological characterisation plays an important role in the decommissioning of nuclear facilities and is central to the planning, implementation and optimisation of decommissioning projects. Effective characterisation allows the extent and nature of contamination to be determined, providing crucial evidence to support facility dismantling, the management of material and waste arisings, protection of workers, the public and the environment, and associated cost estimations.

Because of the important role and significance of characterisation through all phases of decommissioning projects, the Working Party on Decommissioning and Dismantling (WPDD) of the OECD Nuclear Energy Agency (NEA) decided to initiate an expert Task Group on Radiological Characterisation and Decommissioning (TG-RCD). The task group aims to identify and present good practice for radiological characterisation at different stages of decommissioning and to identify opportunities for further development through international co-operation and co-ordination.

The first phase of the task group's work developed strategic guidance for decision makers on the selection and tailoring of strategies for radiological characterisation, and offered an overview of good practices for radiological characterisation at different phases of the life cycle of nuclear facilities (NEA, 2013).

The second (and most recent) phase of the task group's work has explored the practical implementation of characterisation. In particular, it has considered how the selection and tailoring of strategies for the optimisation of nuclear facility characterisation from a waste and materials end-state perspective is applied in practice.

1.1. Aims and objectives

The aim of this report is to identify relevant good practices and to provide advice on the practical implementation of radiological characterisation to support all stages of decommissioning. It also seeks to highlight areas that could or should be developed further through international co-operation and co-ordination.

The primary audience for this report is characterisation practitioners who carry out the tactical planning, preparation and implementation of characterisation to support the decommissioning of nuclear facilities and the management of associated materials and waste arisings. Decision makers are referred in the first instance to the companion phase 1 report entitled "Radiological Characterisation for Decommissioning of Nuclear Installations" (NEA, 2013), which provides more strategic guidance on good practices.

1.2. Scope

The report covers important aspects relating to the practical implementation of radiological characterisation of waste and materials when undertaking the decommissioning of nuclear facilities. It does not cover characterisation associated with routine nuclear operations, characterisation of treated waste, land characterisation or the release of nuclear sites from regulatory controls.

1.3. Approach

The task group used a range of methods to establish learning from the international community relating to the practical implementation of characterisation of waste and materials to support decommissioning. The work has involved:

- a major international survey (questionnaire) to elicit the views of characterisation experts regarding good practice (see Annex A) (NEA, 2016);
- learning distilled from an international conference[1] co-organised by the task group (see Annex B);
- the collation of a series of international case studies (see Annex C);
- the collation and analysis of regulations, standards and guiding documents (see Annex D).

Additional information has been compiled using the knowledge and experience of the task group and their national networks.

1.4. Report structure

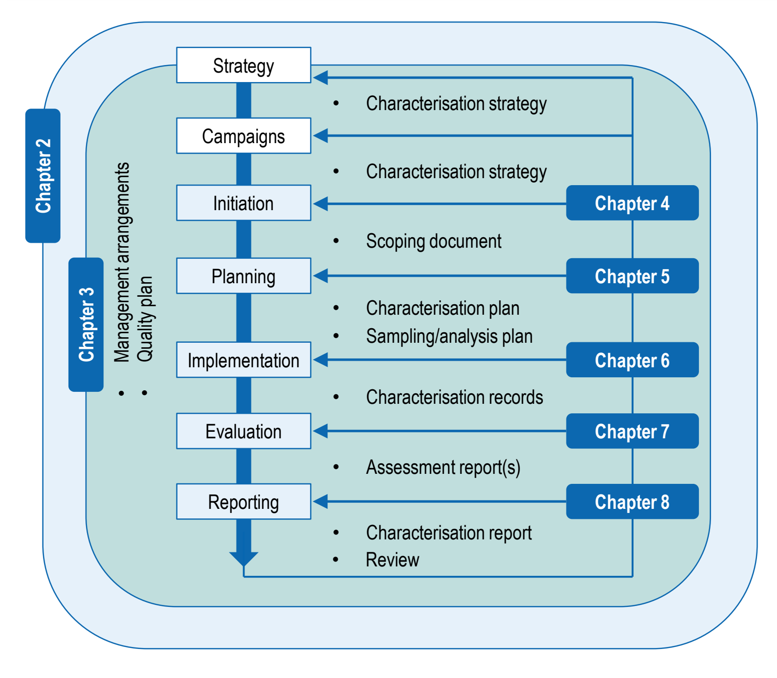
The report describes the characterisation process and compiles the practical learning distilled from all of the task group's work activities according to the structure given in Figure 1.1. Key learning points from the questionnaire and case studies are highlighted within blue and white text boxes, respectively, within the subsequent chapters.

In summary:

- Chapter 2 describes how a characterisation strategy can be used to manage and optimise related characterisation campaigns.
- Chapter 3 summarises the management arrangements and quality assurance that should be applied to all aspects of the characterisation process.

1. International Symposium on Preparation for Decommissioning (PREDEC 2016), Lyon, France, 16-18 February 2016 (www.oecd-nea.org/rwm/wpdd/predec2016).

Figure 1.1: The characterisation process set within a strategic framework, and how it aligns to the structure of this report



Practical aspects of the main phases of the *radiological characterisation process* are described in Chapters 4-8:

- Chapter 4 covers the initiation phase, which should be focused on establishing a general understanding of why characterisation is needed (including the broad characterisation objectives) what knowledge gaps need to be addressed, and on seeking consent from the competent authority, if this is required. The output will be a *characterisation scope document* or the equivalent.
- Chapter 5 sets out the approach to planning, which typically includes: scoping out the problem that the characterisation seeks to answer; developing and refining the characterisation objectives; specifying what characterisation is needed; and understanding how the characterisation information will be used to meet the characterisation objectives. This allows the development of a *characterisation plan,* which includes a specification of the required characterisation and how it will be evaluated.
- Chapter 6 provides details of the implementation phase. This is when the required characterisation work, including inferred characterisation using calculation and modelling, is carried out. This phase will involve monitoring, sampling and analysis, but may also be supported by inferred characterisation

techniques that calculate or estimate the properties and composition of materials/waste, e.g. determination of radionuclide content through activation information or the use of scaling factors. The main outputs from this phase are *characterisation records* containing the characterisation results (e.g. analytical reports).

- Chapter 7 covers the data assessment and evaluation phase. During this phase the characterisation results are interpreted and reviewed against the characterisation objectives. This is likely to include statistical evaluation of the data. The main output will be *characterisation assessment reports*.
- Chapter 8 summaries the final phase of reporting and review, where the overall results are documented detailing how the characterisation objectives have been met and, if necessary, making recommendations to address any gaps. This process should include a review of lessons learnt and ensure that all the characterisation records are stored appropriately to support future characterisation work. The main output will be *characterisation reports* detailing how the characterisation objectives have been met.

Finally, Chapter 9 summaries the conclusions that can be draw from the work, including potential areas for further work and international co-operation.

The detailed supporting evidence from the work activities undertaken by the task group are given in the following annexes:

- **Annex A** summarises the key learning from the detailed and systematic evaluation of the responses to the international questionnaire.
- **Annex B** contains a summary of the International Symposium on Preparation for Decommissioning (PREDEC).
- **Annex C** summarises the key learning from the detailed and systematic evaluation of several international case studies.
- **Annex D** contains a bibliography of international standards and guidance.

1.5. References

NEA (2016), "Radiological Characterisation from a Material and Waste End-State Perspective", NEA/RWM/R(2016)1, www.oecd-nea.org/rwm/docs/2016/rwm-r2016-1.pdf.

NEA (2013), "Radiological Characterisation for Decommissioning of Nuclear Installations", NEA/RWM/WPDD(2013)2, www.oecd-nea.org/rwm/docs/2013/rwm-wpdd2013-2.pdf.

Chapter 2. High-level strategy

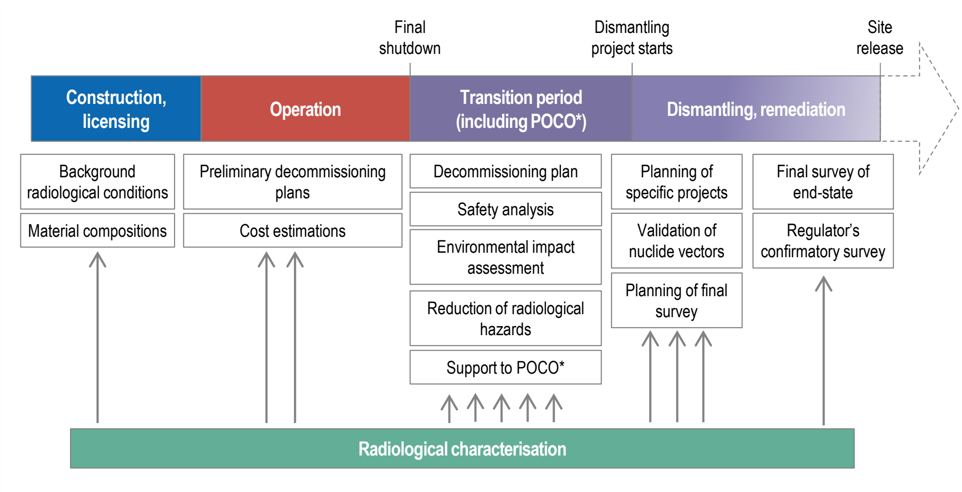
The strategic aspects of characterisation are outlined in the task group's phase 1 report entitled "Radiological Characterisation for Decommissioning of Nuclear Installations" (NEA, 2013) and are not repeated here. This chapter discusses the practical aspects of how a characterisation strategy can help to optimise characterisation in practice.

A characterisation strategy provides an opportunity to consider characterisation across the entire lifetime of a programme or enterprise, considering the inter-relationships between characterisation campaigns, and to set down or reference out to standard approaches defining how characterisation projects will be carried out. This avoids the need to reiterate standard approaches within individual project documentation, helps to ensure that consistent standards are applied and allows the optimisation of characterisation work across an entire work programme. The overall aim of the characterisation strategy is to set out how characterisation objectives can be met in the most efficient and effective manner. This strategic approach may have limited use for discrete and isolated characterisation work but for large programmes there can be very significant savings over the life cycle of the programme. There is increasing recognition that developing characterisation strategies in parallel with major programmes (e.g. decommissioning or waste management strategies) allows a more proactive and optimised approach to be taken to the initiation of characterisation projects and ensures that the right characterisation information is available at the right time to inform decisions regarding the development and implementation of the major programme. As these decisions may relate to the way a facility is decommissioned, the way waste is treated and/or the definition of materials and waste end states, there can be very significant cost, safety and environmental implications associated with delayed or poor quality characterisation information. Practical approaches and the main elements of this strategic management framework are summarised below.

2.1. Life cycle characterisation

A life cycle approach to characterisation provides the opportunity to consider characterisation objectives and timing of characterisation activities across the life cycle of a nuclear facility from design, construction, operation, transition (including post-operational clean-out), decommissioning and waste management through to the end states for materials and waste (Figure 2.1). Characterisation can provide answers to questions and aid decision-making associated with the phase of the life cycle. For example, what is the best way to decommissioning a facility safely while minimising waste? Or it can relate to a transition in life cycle phases, for example, when to stop decontamination processes or how to transport waste for treatment or disposal?

Figure 2.1: Characterisation objectives through a facility life cycle supporting decommissioning and materials, and waste end states



* Post-operational clean-out – the removal of operational materials and waste.

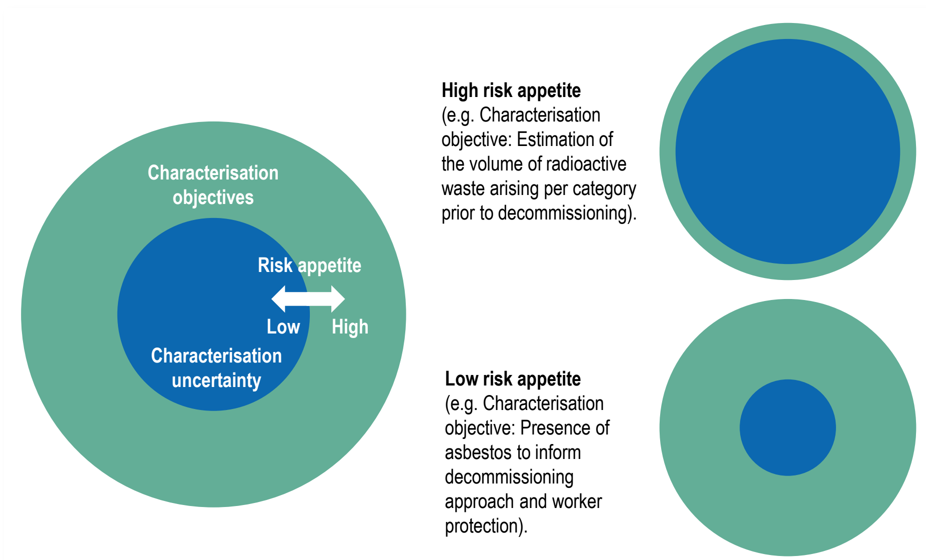
Source: NEA (2013), "Radiological Characterisation for Decommissioning of Nuclear Installations".

The final destination of the material/ waste has always been taken into account in order to optimise the efficiency and effectiveness of characterisation (CS-01; see Table C.1).

A life cycle approach means that, whatever stage in a facility life cycle a characterisation task is being undertaken, best use can be made of all available relevant information, and best consideration can be given to providing appropriate characterisation information that can be used in subsequent stages of the facility life cycle. For example, for a reactor entering decommissioning, design information regarding the composition of construction materials, combined with the operational information, can be used to calculate the expected levels of activation products. In turn this information can be used to optimise what further characterisation information is required, and when, in order to support the subsequent facility decommissioning, waste management and final end states for associated materials and waste. For example, when decommissioning a research reactor in Belgium, characterisation activities in all stages of the decommissioning process were focused on the objectives of the specific stage of decommissioning however, the final destination of the materials and waste was always been taken into account in order to optimise the efficiency and effectiveness of the characterisation work (Annex C, case study 01).

Taking a life cycle approach to characterisation means that there will be a consideration of multiple characterisation objectives and there will be a need to consider what level of uncertainty (or risk appetite) in the characterisation information is acceptable. The uncertainty will relate to the extent of the characterisation work and the accuracy and precision of characterisation results. The risk appetite is likely to vary for characterisation objectives (Figure 2.2). For example, a high risk appetite and uncertainty in characterisation results may be acceptable where the results are informing rough estimates of the volume of radioactive waste arisings per category prior to decommissioning. However, a much lower uncertainty may be acceptable where the characterisation objective relates to the protection of workers because of the consequences of making the wrong decision. Consequently consideration should be given to what characterisation information will be needed to meet specific objectives and to ensure that the level of uncertainty in this information is appropriate. At a detailed practical level this can mean that a characterisation plan may include the use of identical characterisation techniques but the requirement to use different limits of detection and measurement uncertainties depending on which characterisation objectives the results are informing.

Figure 2.2: Illustration of how the acceptable uncertainty in characterisation information may vary with characterisation objectives



2.2. Waste-led characterisation

Waste-led characterisation and decommissioning reduces risk and costs.

In practice, as with a decommissioning strategy, it can be useful to take a waste-led approach to developing the characterisation strategy, working backwards from a waste and materials end-state perspective. This is because often the characterisation requirements at the end of the life cycle are most stringent. However, this approach needs care as there can be very specific and stringent characterisation requirements at any stage of the life cycle, for example meeting the waste acceptance criteria (WAC) for a waste treatment plant with a narrow operating envelope, or meeting specific transport requirements.

Radiological and chemical characterisation must be seen as an ongoing process of high priority and importance. It will only cease after successful execution of the final survey and the termination of the nuclear licence. 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.

2.3. Holistic characterisation

In general, the term "radiological characterisation" represents the determination of the nature, location and concentration of radionuclides in a nuclear facility. It is one of the fundamentals on which to build a decommissioning project. However, properties other than the pure radiological are important and consequently, within both a high-level strategy and characterisation plans, characterisation should be considered in the widest sense covering radiological, physical, chemical and biological properties. For example, characterisation should include understanding the physical dimensions and condition of a facility. This can include the volume and masses of contaminated and potentially contaminated materials, its physical form, structure, geometry, surface coating[1] or the physical properties of waste (e.g. rheology of sludges). The conventional chemical characteristics of a nuclear facility and its associated solid wastes should not be overlooked, as they can significantly impact on the decommissioning plan and the optimisation of waste segregation and disposal plans. Chemical components arise from the composition of the original construction materials, chemicals used in operational processes and chemical spills and incidents associated with the facility. Understanding these are particularly important for worker safety and meeting the specific waste acceptance criteria (WAC) of candidate waste treatment and disposal routes. Important chemical components can be metals, volatile organic compounds and other chemical compounds. For example, understanding the presence and location of asbestos is particularly important to ensure worker safety and to developing the decommissioning plan. Understanding the presence and the chemical form of reactive metals such as sodium, magnesium and aluminium can be very important with respect to waste treatment, storage and disposal. Biological properties may also be important, particularly where decommissioning has been deferred. For example: algal growth in ponds or tanks can create organic rich sludge; bird or bat guano can lead to the generation of the organic rich and biologically hazardous waste streams; and the presence of gas generating microbes within packaged waste has the potential to lead to package deformation and/or early loss of package integrity within interim storage and disposal facilities. All such information is important throughout the life cycle of nuclear facilities, particularly for decommissioning and waste management. This includes the potential for clearance (including reuse and recycling) and meeting acceptance criteria for disposal.

1. The surface coating may have a major impact on the possibility to decontaminate. In addition, surface coating such as zinc may have implications for meeting the waste acceptance criteria for disposal facilities.

Chapter 3. Management arrangements

Radiological characterisation projects will normally form part of a wider work programme or enterprise, such as the decommissioning of a nuclear facility or waste management processes. Multiple characterisation projects may be needed over the lifetime of such programmes. In line with good practice, such programmes generally use integrated management systems, aligned to international standards and guidelines, to manage aspects such as project, people, assets, safety, environment, quality and knowledge. Working effectively with wider stakeholders, partners or contractors is also very important. In addition, there will be specific management arrangements defined which apply to all characterisation work (for example covering characterisation planning or laboratory analysis). A summary of the key areas, with references to good practice is given below.

3.1. Project management

ISO 21500 (ISO, 2012a) provides guidance for project management, however it should be noted that it does not provide detailed guidance on the management of programmes and project portfolios. It is therefore less relevant to the consideration of characterisation strategies. Characterisation projects should be managed in line with such good practice. This includes appropriate planning to define the scope, schedule and costs of the work and then executing the work according to the plan unless authorised changes are agreed. A key aspect regarding the scope is to ensure that all the planned characterisation work will support the delivery of one or more of the characterisation objectives. A major considering for the schedule is how the characterisation work can be undertaken with minimal impact on the wider programme (e.g. decommissioning) not only in terms of work planning but also ensuring that the characterisation information will be available when required to support key programme decisions. As with most projects cost escalation often arises from poor planning of the characterisation work.

3.2. People management

ISO 10018 (ISO, 2012b) provides guidance on engaging people in an organisation's quality management system (see below), and on enhancing their involvement and competence within it. While BS76000 (BSI, 2015) provides a framework which seeks benefit for both organisations and the people who work on their behalf through more equal and sustainable working relationships. Characterisation is a multi-discipline field involving skills in project management, engineering, technical areas (including chemistry, radiochemistry, health physics, statistics, knowledge management, records management, regulation) in addition to well-trained technicians who can ensure that representative samples are taken and repeatable measurements are made. Establishing and maintaining a team of suitably experienced and qualified people is essentially, although the size and make-up of the team will flex through the project. Another key aspect is to preserve and transfer experience and knowledge from the workers who designed, constructed and operated facilities. This is because characterisation planning needs to draw on this knowledge. For example, knowledge of the detailed physical and chemical processes undertaken in the nuclear facility and any significant events during operational life. This knowledge allows inferred characterisation (such as neutron activation modelling) and optimisation of monitoring, sampling and analysis.

3.3. Collaborative working and stakeholder engagement

Stakeholder engagement and working with contractors is an important area of consideration. Stakeholder opinions and expectations must be considered in the decision-making process in order to realise the best outcome and to minimise the risk that the characterisation work will not meet its objectives. Providing too little information may lead to unfounded expectations. Paucity of information, or poorly presented information, may lead to distrust and/or loss of credibility. Therefore stakeholder participation process must be co-ordinated and discussed with the stakeholders from the outset of the characterisation work. When working with contractors there is a need to engage early and seek to work collaboratively. The same is true for regulators, particularly when they will need to take regulatory decisions informed by the characterisation information. A good means to achieve this is to develop (with all relevant stakeholders), implement and maintain a stakeholder engagement plan from the start of the characterisation work. ISO/DIS11000 provides a guide for organisations covering the requirements of a strategic life cycle framework to establish and improve collaborative relationships in and between organisations.

3.4. Asset management

ISO 55001 (ISO, 2014) set out the requirements for asset management for plant and equipment. This standard is relatively new and is not yet adopted widely. For characterisation, the major assets are associated with in situ measurement equipment, sampling equipment and laboratory analytical equipment. Consideration should also be given to the information technology asset that contain the characterisation records and information (see Section 3.8) as preservation of the valuable information it contains is essential. Key aspects are:

- ensuring maintenance schedules are in place and adhered to in terms of scope and frequency, in line with those defined by the supplier/manufacturer or a defined technical basis of maintenance;
- having documented maintenance procedures, including scheduled services and checks;
- undertaking services and intermediate checks to ensure satisfactory continuing operation;

- ensuring resilience through contingency arrangements, including preventative maintenance, the availability of spare parts and an equipment replacement programme.

3.5. Environmental management

The international environmental management standard ISO 14001 (ISO, 2015a) is now widely adopted and it is expected that most characterisation projects will be undertaken within this framework. Characterisation plays a key role in environmental management for example informing the development and maintenance of an environmental aspects register. Some more specific environmental considerations for characterisation projects are associated with waste management. Characterisation is key to facilitating the implementation of waste-led decommissioning and the waste management hierarchy. For example, good facility characterisation, used to support the facility decommissioning plans can allow deconstruction to take place in a manner that prevents/minimises the generation of radioactive waste. Characterisation is also fundamental to ensure that wastes are appropriately consigned for reuse, recycle, treatment or disposal.

3.6. Safety management

ISO 45001 (ISO, forthcoming) and an ISO international standard for occupational health and safety is currently being developed and is expected to be published by the end of 2017. It aims to provide a framework to improve employee safety, reduce workplace risks and create better, safer working conditions and will take into account other international standards in this area. International radiological protection standards are developed by the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA). Radiological characterisation activities in situ may cause significant personal exposure. A particular consideration for characterisation is the taking of measurements and samples in unfamiliar areas where the levels of radiation made be poorly known and, in the case of decommissioning, the facilities made be old and in degraded conditions. Key characterisation objectives are often associated with understanding the composition and form of radioactive and hazardous substances so that appropriate worker safety protective measures can be put in place during decommissioning or waste handling operations. However, for all characterisation activities radiation doses to workers must be below legal limits and, through a process of optimisation (considering measures such as time, distance, shielding and personal protective equipment) reduced to as low as reasonably practicable. This involves weighing up the worker dose detriments versus the benefits derived from meeting the characterisation objectives. In areas with unknown or high dose rates, or levels of contamination, alternative ways to assess the radiological status should be considered, such as remote characterisation techniques. In such situations it may be useful to undertake initial surveillance work to establish the general dose rates/contamination levels before deciding on the more detailed characterisation techniques which will be employed.

3.7. Quality management

> Characterisation campaigns should have a dedicated quality assurance plan developed early in the characterisation process.

The international quality standards ISO 9001 (ISO, 2015d) is widely adopted and it is expected that most characterisation projects will be undertaken within this wider framework. Any organisation collecting and evaluating characterisation data must be concerned with ensuring the right characterisation information has been collected and the results and their evaluation is of an appropriate quality. This will ensure that the characterisation objectives can be met. This requires appropriate control of technical, administrative and human factors. While the wider management arrangements already discussed should deliver appropriate control, establishing and implementing a quality plan is a means to ensure this is the case. The quality plan can consider the entire characterisation process and assess the more important and higher risk aspects. Quality assurance and control measures can then be put in place to mitigate against errors. Such measures may include: audit, inspection, validating or verifying information, independent review. In the case of analysis this can include equipment calibration and checks; control sample and analysis ensuring results are traceable, inter-laboratory exercises and the analysis of references materials. Many laboratories now use methods which are independently accredited to ISO 17025 (ISO, 2015b). Consideration should also be given to how the quality of the assessment and evaluation (including geo-statistical techniques) of characterisation information can be ensured.

3.8. Record and knowledge management

> Characterisation records management is essential since years and decades may pass between characterisation campaigns and the generation of waste and final disposal.

There is increasing recognition that there are significant benefits from a structured approach to managing knowledge and an international standard ISO 30401 (ISO, forthcoming) is currently under development. Knowledge management is a combination of processes, actions, methodologies and solutions that allow maintaining, sharing, accessibility and development of object-oriented knowledge. Characterisation processes will benefit from such processes because they use a broad range of knowledge ranging from information about the construction of nuclear facilities to their operational history and decommissioning in addition to characterisation results and evaluation reports. More specifically good records management is essential for characterisation. ISO 15489 (ISO, 2016) and ISO 30300 (ISO, 2011) are key standards in records management and are aligned with other management system standards e.g. ISO 9001 (ISO, 2015d) and ISO 14001 (ISO, 2015a). All organisations should have information asset registers which list the information or records which forms the basis of a records retention schedule. Characterisation information and records are a particularly important part of these wider records and retention periods should be defined considering business, legal and national/international obligations. Some characterisation records may need to be kept for many years; for example, the primary records associated with characterisation of higher activity waste which is destined for disposal in a geological repository. Records may be stored in many forms (e.g. paper, microfilm, electronic) and storing them in more than one form and in different locations provides resilience. Experts in digital preservation currently recommend the use of PDF Archive format in order to stand the best chance of preserving records in electronic format.

3.9. Security and transport

Security and transport management arrangements can also be very important considerations. For example, where characterisation is performed by remote laboratory and where the characterisation involves special nuclear materials. In these situations advice should be sought from competent specialists.

3.10. References

BSI (2015), *Human Resources, Valuing People, Management System, Requirements and Guidance*, BS76000, BSI, London.

ISO (forthcoming), *Human Resource Management – Knowledge Management Systems – Requirements*, ISO 30401, ISO, Geneva.

ISO (forthcoming), *Occupational Health and Safety*, ISO 45001, ISO, Geneva.

ISO (2017), *Collaborative Business Relationship Management – Framework*, ISO/DIS11000, ISO, Geneva.

ISO (2016), *Information and Documentation – Records Management Part 1: Concepts and Principles*, ISO 15489, ISO, Geneva.

ISO (2015a), *Environmental Management*, ISO 14001, ISO, Geneva.

ISO (2015b), *General Requirements for the Competence of Testing and Calibration Laboratories*, ISO 17025, ISO, Geneva.

ISO (2015d), *Quality Management Systems – Requirements*, ISO 9001, ISO, Geneva.

ISO (2014), *Asset Management – Management Systems – Requirements*, ISO 55001, ISO, Geneva.

ISO (2012a), *Guidance on Project Management*, ISO 21500, ISO, Geneva.

ISO (2012b), *Quality Management – Guidelines on People Involvement and Competences*, ISO 10018, ISO, Geneva.

ISO (2011), *Information and Documentation Management Systems for Records – Fundamental and Vocabulary*, ISO 30300, ISO, Geneva.

Chapter 4. Characterisation initiation

The initiation of a characterisation project and the subsequent planning of characterisation activities, are fundamental to any systematic approach to characterisation. These initial steps are considered crucial to ensure that the right characterisation information is available at the right time, and the characterisation objectives are well defined and can be delivered. Initiation should be undertaken within the framework of a *characterisation strategy* (Chapter 2) and relevant management arrangements (Chapter 3).

> Characterisation objectives should be defined at the initiation phase in a characterisation plan or strategy.

Often the need to initiate a characterisation project will arise in reaction to the development of wider strategies and plans (e.g. decommissioning or waste management plans) and the identification of knowledge gaps. However, there is increasing recognition that developing characterisation strategies in parallel allows a more proactive and optimised approach to be taken to the initiation of characterisation projects (Chapter 2). The initiation of any characterisation project should be focused on establishing a general understanding of why characterisation is needed and what knowledge gaps it is seeking to address. This is critical as it provides the basis for all subsequent phases in the characterisation process. In the absence of a characterisation strategy, it is still worthwhile considering what future knowledge gaps the planned characterisation work might address. For example, a characterisation campaign to inform how to dismantle a nuclear facility has the potential to provide significant information to support the development of associated waste management plans.

4.1. Initial characterisation scope and objectives

In broad terms the outcome of the initiation phase will provide an outline of the scope of characterisation that is required, including the reasons why the work is needed according to the objectives of the project. Table 4.1 provides some typical characterisation objectives and provides an indication of the scope (extent and level) of characterisation required. This information will then be used in the planning phase. This may already be documented in a characterisation strategy. However, in the absence of a characterisation strategy, and/or where the characterisation planning process will be contracted out, the outcome of the initiation should be documented. This may take the form of a *characterisation scope document* or equivalent. This provides the business case for proceeding to the characterisation planning phase and it can form the basis of a "contract specification" where the characterisation work is intended to be out sourced. All relevant stakeholders should be consulted on the content of this document and if appropriate consent or approval from the competent authority should be sought and gained.

During the characterisation project, additional constraints may be realised and/or the scope may change. It is important to track and review any changes which may impact on the characterisation approach and may consequently alter the objective(s) and a wider characterisation strategy (if this exists). Therefore, maintaining an up to date initiation scope document (and/or characterisation strategy), is a useful tool in maintaining "focus" and provides the underpinning for why the characterisation work is being carried out.

Table 4.1: Typical characterisation objectives, extent and scope

Objectives	Extent	Scope
Support development of decommissioning strategy (application of dismantling steps)	Facility (all systems, buildings and areas)	• operational history; • facility construction and materials composition and volume; • activation calculations; • dose rates; • total radioactivity distribution; • key radiological and non-radiological contaminants.
Risk assessment	Main activated/contaminated areas	• past events; • inventory within systems, tanks, etc.; • nature of inventory fixed or mobile.
Preparation for post-operational clean-out/decontamination	Primary circuit (without damage), systems, tanks, effluent treatment systems and waste packages	• key radiological and non-radiological contaminants; • dose rates; • total radioactivity distribution; • contamination depth.
Estimation of waste volumes per category	Systems, building structures, radioactive and hazardous waste	• operational history; • facility construction and materials composition and volume; • activation calculations; • total radioactivity distribution; • key radiological and non-radiological contaminants; • applicability of volume reduction techniques.

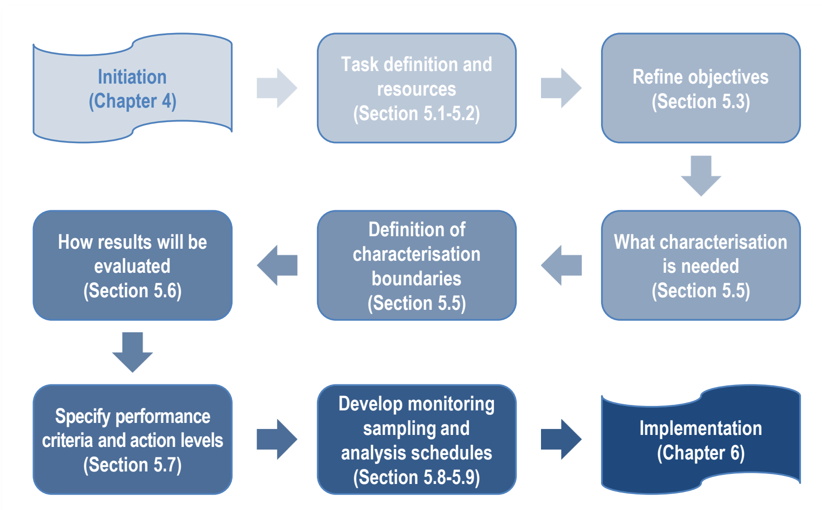
Table 4.1: Typical characterisation objectives, extent and scope *(cont'd)*

Objectives	Extent	Scope
Worker protection, work permissioning	Buildings, systems and components, waste, residues, sludges dependent on nature of work	• previous radiation surveys; • dose rates; • alpha-contamination levels; • asbestos; • presence of pathogens; • presence of chemical toxins.
Categorisation and sentencing of waste	Waste arisings	• previous radiation surveys and other provenance; • determination of scaling factors; • consideration of heterogeneity and inaccessible areas; • detailed surveillance of waste supported by scaling factors and consideration of uncertainty; • chemical characterisation/ surveillance.
Clearance of the buildings	Surface (and subsurface) of the buildings/site. Buried systems and components	• previous radiation surveys and other provenance; • determination of scaling factors; • detailed characterisation supported by scaling factors, as available and appropriate; • surface contamination/activation levels and activity concentrations; • consideration of surface contamination and activity concentrations; • consideration of contamination penetration/mobility behaviour and potential for contamination in inaccessible areas.

Chapter 5. Characterisation planning

As with the initiation phase (Chapter 4) of a characterisation project the planning phase is fundamental to the success of the work and must be undertaken within the framework of a *characterisation strategy* (Chapter 2) and relevant management arrangements (Chapter 3). When planning characterisation there are some important general approaches that can be used to optimise the work required. These, together with practical guidance, are summarised below. The outcome from each step should be documented, typically in a *characterisation plan* (Figure 5.1).

Figure 5.1: Characterisation initiation and planning



The planning phase of characterisation should be focused on why, what and when characterisation is needed in order to meet well-defined characterisation objectives. In addition, an understanding of the how the characterisation will be implemented and the related resources, timescales and costs. The planning phase should be commensurate to the complexity of the task with the level of characterisation effort being proportionate to the characterisation objectives and the specific decisions that the characterisation information will inform. The outcome will be an appropriate characterisation plan which ensures that the characterisation objective will be achieved, in an optimised manner.

There are a range of ways in which a characterisation project might be planned. An established approach is to follow the principles of data quality objectives (DQO) process. This characterisation planning process was developed by the US Environmental Protection Agency (EPA, 2006) for use with contaminated land, but the principles can provide a structured planning process for any characterisation project. The key steps in systematic characterisation planning are given in Figure 5.1 and broadly follow the steps within the DQO approach. The steps are summarised below together with practical guidance. It is important to note that while there is a need for systematic planning the process may not be linear, and in some situations can be an iterative process during which it may become necessary to go back to previous steps as new data and information become available. The investment of time and effort in the planning stages should ensure that there is clear justification for data collection, analysis and interpretation and that the characterisation objectives are met.

5.1. Task definition and collation of existing information

> Good characterisation planning based on accurate evaluation of historical data can reduce time and cost and directly affect the entire approach to decommissioning (CS-02 and CS-12; see Table C.1).

The starting point is to review the outcome from the initiation phase, which will have scoped out the reasons why characterisation is needed. This will involve understanding of the work (e.g. decommissioning or waste management) that the characterisation is intended to support or inform, including its scope and duration. In addition, relevant *provenance and precedence*[1] needs to be collated and the quality of such information understood. Work may be required to correlate, verify and/or interpret such information. Operational history and facility/site documentation are seen as most useful to support characterisation plans as these guide where to characterise and what to characterise for. Previous characterisation results, inventory data and interviews with operating personnel are also important information. Conceptual models and site visits can be useful to visualise the characterisation needs.

> Important information includes: facility documentation, operational history, knowledge from facility staff, previous characterisation results and inventory data.

It is wise to consider from the outset all future characterisation needs associated with downstream work or associated projects. This will help to ensure that opportunities to maximise the use of the characterisation information generated are realised and the need for future characterisation campaigns is minimised. Overall the information gathered should provide a general understanding of the type of characterisation data needed and will allow the

1 Provenance – knowledge of the use (including location) and controls which have been applied to an article or substance to determine its potential to have become activated and/or contaminated by radioactivity, and the nature of any potential activation or contamination. Precedence – data, documentation and experience collected from sites who have previously undertaken relevant characterisation work drawing comparisons and learning from good practice and areas for improvement.

formation of a "*problem statement(s)*". An example for a facility decommissioning project might be "*In order to support the safe decommissioning of the nuclear reactor, while minimising radioactive waste, and appropriately managing waste arisings, characterisation data is required to determine the extent, nature and levels of contamination and activation*".

5.2. Resource planning and stakeholder engagement

Assembling a planning team with appropriate skills and identifying and engaging with all stakeholders who are influential in the characterisation processes exercise is essential. This could include project managers/planners, engineers, technical specialists, sampling technicians, chemists, statisticians, staff responsible for quality assurance and regulatory compliance and stakeholders with responsibilities/interests in how the characterisation information is used. These wider stakeholders may include: facility/waste owners, decommissioning and waste management (including treatment, storage, transport and disposal) project managers, waste receivers and competent authorities/regulators. For high profile projects this may include central and local government representatives and members of the public. These stakeholders must be appropriately included and consulted throughout the characterisation process. A good way to achieve this is to develop and implement an agreed *stakeholder plan* from the outset detailing who will be consulted, what they will be consulted on and when the consultation will occur. At this stage it is also worth considering the resources and expertise needed to continue to plan the work, including costs and timescales to ensure that characterisation information can be provided to meet the required needs. Such checks can avoid costly delays to the associated projects such as decommissioning or waste treatment and allows the early exploration of alternative approaches.

Secure early involvement of decision makers and stakeholders. Getting acceptance from all stakeholders and contributors is crucial (CS-08; see Table C.1).

5.3. Refining the characterisation objectives

It is crucial to refine and record the characterisation objective(s) by defining more specific objectives which will answer key decisions or address significant knowledge gaps. It may be useful to define these as questions and with alternative outcomes based on the results of the characterisation work. Examples might be "*Are the decommissioning arisings radioactive waste? If yes decontaminate or dispose of as radioactive waste. If no – manage as non-radioactive materials/waste*" or "*Are the radiation levels too high to allow manual decommissioning? If yes use remote dismantling. If no – use most efficient dismantling techniques*". Using a characterisation life cycle approach this is likely to result in a large number of characterisation objectives against which any characterisation

The characterisation campaign helped to define the dismantling method, to evaluate waste management options, determine the impact on workers and the public, to support design reviews of the conditioning and disposal facilities (CS-02 and CS-06; see Table C.1).

can be optimised in order to provide the right information at the right time and to the right quality. The international questionnaire (Annex A) revealed that during decommissioning planning the most important characterisation objectives are those that contribute towards the development of the decommissioning and waste management (prevention/minimisation, storage, treatment, transport and disposal) plans, as well as cost estimation and safety analyses. Once dismantling is taking place the primary objectives of radiological characterisation become waste and hazard management, with waste management generally being most important with the exception of large, and significantly contaminated, facilities/sites.

5.4. Characterisation information required

Based on the established characterisation objectives and the information already available, the new characterisation information needs can be defined. This involves considering what radiological, physical, chemical and possibly biological information is needed and the means to provide it. At this stage key aspects will be the contaminants concerned and the monitoring, sampling and analysis techniques that will be required. This must be informed by an understanding of the quality of characterisation information the techniques can provide, for example the accuracy/precision and limits of detection, and whether the characterisation objectives can be meet. In practice this can be established through a consideration of the performance/acceptance criteria associated with the characterisation objectives for example waste acceptance criteria (WAC) associated with waste storage, treatment and/or disposal are likely to be highly relevant to this process. Regulatory requirements (for example associated with waste categorisation criteria; transport regulations and the protection of workers) are also likely to be important.

Requirements to analyse some non-radiological hazards are identified in the objectives to enable early project planning (CS-13; see Table C.1).

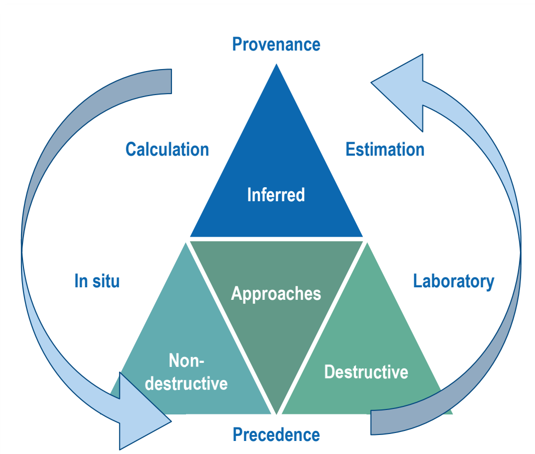
At this stage it is worth checking whether additional characterisation is required, or whether the characterisation information already available can be used to meet some or all of the characterisation objectives. Where characterisation is needed there needs to be a consideration of the best available techniques to provide it. In broad terms characterisation information can be delivered: by inference (e.g. calculated in the case of activation products or estimated indirectly from other characterisation information); through non-destructive (and often using in situ) techniques; or via destructive analysis typically in a laboratory (see Figure 5.2). Often a combination of approaches will provide the most efficient and effective approach. For example, activated reactor waste may use inference (activation calculations) to broadly assess the expected radionuclides present and their associated activity concentration. However, this must be validated and potentially refined through detailed sampling and laboratory analysis which allows the development of scaling factors for easy-to-measure

Cobalt-60 and Ceasium-137 are the preferred (easy-to-measure) radionuclides for use with scaling factors.

A combination of measurements and calculations will produce a rational estimation of radioactivity in an efficient way (CS-03 and CS-06; see Table C.1).

radionuclides (typically abundant gamma emitters) relative to more difficult-to-measure radionuclides. The scaling factors can then be used with in situ measurements (typically gamma spectrometry) of easy-to-measure radionuclides to rapidly determine the inventory/activity concentrations of all radionuclides present in materials or waste.

Figure 5.2: Characterisation approaches



More detailed consideration is also needed at this stage regarding what types of samples will be taken (e.g. metal, concrete) what specific analytical techniques will be used, how many samples are required, how long the analysis takes, how much it will cost and whether this can or will be undertaken within the organisation or require letting a contract to an external specialist supplier.

5.5. Refining the characterisation scope (boundaries)

The evaluation of characterisation results is typically based on understanding the characteristic from a "population" of characterisation results and using this information to interpolate/extrapolate to the entire materials/waste but within defined boundaries. These boundaries can be spatial, temporal or material specific but typically for decommissioning and waste management, the spatial and material boundaries tend to be most important. For example, zoning is often used to try to establish areas in terms of their radionuclide composition as this allows the use of scaling factors. The zoning takes into account factors such as different types of material of waste and/or spatial areas that may become contaminated or activated in different ways.

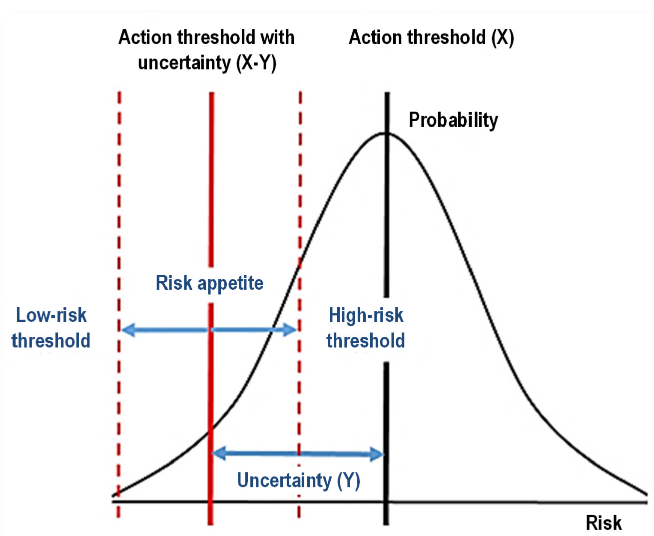
Characterisation planning used historical information, activation modelling and preliminary characterisation to define similar radionuclide vector grouping of materials so as to allow the use of a scaling factor methodology (CS-02 and CS-12; see Table C.1).

However, while factors such as radioactive decay can be compensated for, time boundaries can be important particularly where some of the contaminants are mobile and relative composition of contaminants/radionuclides can change. This means that the validation of characterisation information with respect to time, space and materials is very important, particularly when using indirect methods such as scaling factors. There may also be other assumptions, constraints or limitations that can impact and/or influence the characterisation approach such as the available timeline, available funding, restricted access to data or for sampling (e.g. resulting from inaccessible areas such as the internal surfaces of pipes and vessels) and national context, in particular the regulatory framework. It is important to define and record the boundaries, assumptions and constraints in order that the characterisation information is understood and evaluated in the right context.

5.6. Defining how characterisation information will be evaluated

For each population of characterisation results there is a need to understand how these will be evaluated. It is common practice to set thresholds linked to actions. These action levels should be linked to the characterisation objectives and more specifically to the questions and alternative actions specified around characterisation objectives. This allows quantitative decision-making linked to the characterisation objectives. Using the example given above a quantitative decision might be *if the radionuclide concentrations is ≥ XBq/g then decontaminate or dispose of as radioactive waste. If < XBq/g then manage as non-radioactive materials/waste*, where X equals the activity concentration boundary at which waste is considered to be radioactive (see Figure 5.3).

Figure 5.3: Determining the decision and action levels while taking account of uncertainty and appetite for risk



5.7. Managing uncertainty and risk

When setting such action levels it is very important to consider the uncertainty in the characterisation information. In most cases underestimation of contaminants tends to be the greatest concern however, overestimation can be costly. This area is commonly overlooked which can lead to significant problems. To avoid such matters the variability in a population of characterisation results needs to be considered taking into account all significant sources of uncertainty. Extending the example above, the quantitative decision becomes *if the radionuclide concentrations is ≥ (X-Y) Bq/g then decontaminate or dispose of as radioactive waste. If < (X-Y) Bq/g then manage as non-radioactive materials/waste,* where Y equals the overall uncertainty (at a specified confidence level). Once the variability has been established, this can be combined with an understanding of the implications of making the wrong decision. This can be folded into the action level and associated decision-making. For example, a more stringent action level may be defined, taking greater account of uncertainty (using a higher confidence level), where the characterisation objective is to determine whether waste is radioactive waste or not. This is because there is likely to be a lower appetite for risk associated with mis-consignment of waste as non-radioactive because the implications can be significant from a safety, environmental, legal, reputational and cost perspective (Figure 5.3). Statistical modelling and data visualisation techniques are often used to determine the scope of the characterisation information needed (i.e. the number of monitoring, sampling and analysis) to ensure that the evaluation of the characterisation results will be valid.

5.8. The characterisation plan, including monitoring, sampling and analysis

Normally the outcome from the planning process is a *characterisation plan* (sometimes referred to as a sampling and analysis plan). Consequently, a typical characterisation plan will include summary information from the early planning steps, i.e.:

- Why the characterisation is needed – referencing a characterisation strategy (where available), summarising the scope and problem the characterisation work seeks to address, who should be involved and setting out the main characterisation objectives.
- What information already exists – including past characterisation information as well other relevant information, such as facility operational records, that will inform whether and what future characterisation is needed.
- How the characterisation data will be evaluated and used to meet the characterisation objectives – including the use and validation of scaling factors (if used) and taking account of uncertainty and risk.

The characterisation plan will also include detailed specifications which set out what characterisation work is required. The precise specification of what is required will be based on all of the earlier planning steps and should consider physical, chemical and biological as well as radiological characterisation. This typically takes the form of detailed monitoring, sampling and analytical schedules which are often then used to secure third party contractor support to undertake the characterisation work. Time and effort should be taken to fully engage with monitoring, sampling and laboratory staff to ensure the requirements are fully specified, understood and are achievable, including within the available time and planned costs. Significant problems can develop at this stage if the specifications are not clearly defined and the contractor support has not been engaged from the initiation of the work. Key aspects to consider when developing such schedules are:

> A detailed and systematic characterisation plan should be developed, including what samples and measurements are required and what analyses should be undertaken.

- **Monitoring**: Number of monitoring locations required, use of unique monitoring location identifiers; monitoring locations; date and time of monitoring; use of specific monitoring techniques to ensure representative results (this could include ensuring a defined detector/source geometry is used and for non-specific radionuclide techniques checking that interference from other radionuclides is not occurring and that the detector calibration is appropriate).
- **Sampling requirements**: Number of samples required, use of unique sample identifiers; sample locations; sample matrices; sufficient sample mass/volume to support the analytical needs; date and time of sampling; use of specific sampling techniques to ensure representative samples (this could include the specification of parameters such as sampling depths and methods to prevent losses of volatile radioactive or hazardous substances); sample transport, preservation and retention (this could include sample containers and containment, shielding, refrigeration, etc.); use on any specific sampling pre-analysis techniques including constraints (for example to ensure sample homogeneity and prevent losses of determinants); recording any significant deviations from the sampling requirements.
- **Analysis**: Determinants required for each sample and/or sample type (matrix); required level of uncertainty and limits of detection; use of unique analysis identifiers traceable to the unique sample identifiers; use of specific analytical techniques; recording any significant deviations from the analytical requirements.

The monitoring, sampling and analysis approach (strategy) is informed by the characterisation objectives (Sections 4.1 and 5.3), how the results will be evaluated (Section 5.6) and the acceptable level of risk and uncertainty (Section 5.7). The compiled *provenance and precedence* (see Section 5.1) can also inform this process but often pilot or test characterisation work (see Section 5.9) is required to reduce uncertainties such as radionuclides/contaminants present, the broad levels of contamination present and the degree of heterogeneity of contamination. In summary terms there is a need to ensure that the measurements (and samples) will be representative of the materials or waste being characterised and provide characterisation results can be evaluated and will provide statistically valid and meaningful results. Specific guidance can be used to inform this process (NRC, 1998).

All monitoring, sampling and analytical information should be logged, including who undertook the work, to ensure that the characterisation data is traceable. For example, *change of custody forms* should be used to manage sample transfers, sample records and analytical reports to confirm sample and analytical integrity.

A *characterisation plan* should cover how characterisation records will be managed, including how they are made, stored and retained for future use. This will need to consider regulatory and business requirements. Certain records may be required to be retained for a very long-time e.g. records associated with higher activity waste where disposal and the disposal site closure may not occur for many decades. Consideration should also be given to how the health and safety (including radiological protection) of people undertaking the characterisation work will be ensured and how any wastes arising from the characterisation process will be managed.

A *characterisation plan* should also set out how the quality of the characterisation information will be ensured or reference out to an associated characterisation quality plan (see Section 3.7) or to separate quality plans (e.g. covering sampling or laboratory quality plans). Whichever approach is taken it is important that all the critical steps of the characterisation process that could impact on quality of the characterisation are considered.

5.9. Verification of the characterisation plan

An internal dedicated review process is essential to ensure that characterisation gives statistically robust and representative results. Review by external experts is also important.

Once the characterisation plan has been finalised, it is worth undertaking a review to ensure that all of the proposed characterisation work supports the characterisation objectives and the evaluation process will provide the information required to address knowledge gaps and inform decisions. This should be undertaken seeking to optimise monitoring, sampling and analysis while ensuring all objectives will be met. This will avoid the generation of characterisation information of limited or no specific use and the need for repeat characterisation which is costly, can generate additional waste and can result in additional worker doses. It is also worth considering when and how the required characterisation work can be undertaken most efficiently. This is likely to involve the interactions with operational, decommissioning and/or waste management plans. Undertaking some pilot or test work to confirm all aspects of the proposed approach (covering both implementation and evaluation) can be very useful at this stage. In addition, seeking independent external review of the characterisation plan at this stage can be very valuable.

Finally, it is important to draw out the benefits of the characterisation which are often substantial but not fully recognised. For example, a waste treatment process designed on the basis of little or poor waste characterisation information can result in the construction of a superfluous waste treatment facility incapable of treating waste with unrevealed properties (for example pyrophoric material or the potential generation of explosive or expansive gases). Additional benefits may be realised that are not aligned to the immediate "problem". It is particularly important to consider how all or some of the characterisation information may help to resolve future problems and support future and

Good characterisation planning based on accurate evaluation of historical data can reduce the time and cost, and directly affect the entire approach to decommissioning (CS-02 and CS-12; see Table C.1).

wider decisions with reference back to the characterisation strategy and wider decommissioning and waste management plans. This will ensure that the characterisation plan commands wider support, including the finances required and can be implemented.

5.10. References

EPA (2006), "Guidance on Systematic Planning Using the Data Quality Objectives", EPA QA/G-4.

NRC (1998), "A Nonparametric Statistical Methodology for the Design and Analysis of Final Status Decommissioning Surveys", NUREG-1505, Revision 1.

Chapter 6. Characterisation implementation

The implementation stage is when the characterisation work is carried out. What characterisation is to be undertaken and how it will be implemented should be clearly specified in the *characterisation plan* which is prepared during the planning and initiation phase.

6.1. Prerequisites for characterisation implementation

Before implementation of characterisation activities can begin several factors must be considered.

A fundamental prerequisite is ensuring the health and safety of workers. The potential hazards associated with the facilities to be characterised and the risks associated with undertaking the characterisation work must be identified and appropriate action taken to prevent or minimise these. This will include conventional hazards which may be significant if the facility is aged and has been left to degrade over a number of years. It is likely that some areas may not have been designed to allow worker access and therefore gaining access will require careful planning in order to ensure worker safety.

Consideration of the health and safety of workers involved in characterisation is a fundamental prerequisite.

In addition, the risks associated with radiological exposure of workers must be understood and justified before commencing any planned activities. Appropriate dose monitoring arrangements must be implemented including specified limits, supply of dose recording and alarmed equipment and recording of worker doses. In all cases the hazards, both conventional and radiological, must be identified and justified before proceeding with the plan. If work cannot be justified then the characterisation plan should be amended to reduce the risk or eliminate the hazard. For all work activities workers must be supplied, and trained to use, the appropriate personal protective equipment including suitable dosimetry equipment. A fundamental consideration should be whether and to what extent remote and/or automated characterisation techniques for monitoring and/or sampling can be employed which avoid the exposure of workers to risk. There is increasing use of robotic devices. For example, drones (Martin et al., 2016) and remotely operated vehicles, including submersible devices (Pyne et al., 2015), have been used to undertake characterisation work. Such techniques can have other benefits including lower costs and the ability to access, inspect, sample and decontaminate inaccessible areas (for example, the internal surfaces of pipes or vessels using pipe crawlers [SRR, 2015]).

A wide range of characterisation activities may be implemented as part of characterisation plan. These activities may include area preparation, in situ measurements, sample collection and laboratory analysis using a wide variety of equipment. Work instructions must be developed and maintained to cover these activities. These procedures should include definitions and responsibilities for field and laboratory personnel who will undertake the work, how to calibrate/check/use equipment, the procedure for taking samples and process for transferring custody of samples. Development of the operational procedures will be informed by the information contained in the *characterisation plan*, including the number, type and location of sampling and measurements to be undertaken. Documentation, records management and reporting requirements should also be clearly specified.

Workers undertaking characterisation activities must be suitably trained and qualified.

Workers must be suitably trained and qualified to carry out the activities which they will be performing. The necessary level of training should be identified for each activity and all equipment. A training programme should be developed which will ensure the workers involved are provided with the required training and that this is maintained as necessary to fulfil the activities as specified in the *characterisation plan*. Training records should be maintained to identify which workers have passed the training requirements and can undertake each activity.

Characterisation work is often contracted out. This can include all of the work or specific aspects such as sampling and laboratory analysis. In these circumstances a *technical characterisation specification* should set out the purpose, scope and description of the required work. It should also detail the technical requirements such as procedures, field and laboratory instrumentation to be used, quality control measurements and reporting requirements. Potential contractors should be evaluated to determine their ability to perform the necessary operations. For large or complex sites, this evaluation may take the form of a pre-award audit. For less complex sites or facilities, a review of the potential service provider's qualifications may be sufficient for the evaluation. In any case, all the service providers, contracted or in-house, should have an active and fully documented quality system in place. If the work is being carried out internally the *characterisation plan* may contain sufficient specification of the work but it can be supplemented by an internal work instructions or service level agreement.

Another important prerequisite before commencing characterisation is to acquire consent from the site owner and to ensure that any specific requirements of the owner are met.

Consideration of these prerequisites allows any final adjustments to the characterisation plan to be made.

6.2. On-site preparation for characterisation work

Before starting the execution of characterisation work it is necessary to inspect and prepare the sampling and measurement locations. This is important as if problems with access, or additional hazards, are identified it may lead to a requirement to reconsider the operation and amend the *characterisation plan*. It is worth noting that new techniques using virtual reality are being used to simulate operations in complex facilities, where access for characterisation might be difficult, in order to optimise the sampling and measurement operations when they are actually undertaken.

It's important to understand the area to be characterised and adapt the original characterisation plan if necessary.

It is also often worthwhile assembling the team that will undertake the characterisation work and evaluate the results for a site visit prior to the work commencing. This may include: the project manager, measurement and sampling technicians, a laboratory representative, characterisation experts and other specialists and stakeholders, as appropriate. This site visit provides a visualisation of how the work will be carried out and informs the context in which the characterisation results will be evaluated. A walk down will also help to identify any problems with accessibility resulting from any physical and/or radiological factors and what additional actions need to be taken. This could include, for example, tag-out some equipment, removal of the insulation, changes in the sampling sequence and/or the elimination of sources of interference. Ideally site visits should be performed as part of the planning stage and repeated prior to implementation to check that nothing has changed.

The external exposure rates or radioactivity concentration of a specific sample may limit the time that workers will be permitted to remain in the area, or may dictate that smaller samples be taken and special holding areas be provided for collected samples prior the shipment. These special handling considerations may conflict with the size specifications for the analytical method, normal sampling procedures or equipment. There is a potential for biasing sampling programmes by selecting samples based on the safe handling limits of transportation regulations.

In some situations the field conditions differ significantly from the equipment calibration assumptions and a special calibration for a specific field conditions may be required. For example background levels of radiation may be different. If responses under routine calibration conditions and proposed use conditions are significantly different, a correction factor should be applied. The testing of field instrumentation should allow the setting of the applicable operating parameters such as the measurement time and the detector/source geometry.

The scope of the execution typically includes:

- Installation and removal of the necessary infrastructure to allow the characterisation work to take place. This may involve the removal or installation of: scaffolding, insulation, containment, bunding, temporary enclosures, facilities to decontaminate tools, electrical supply, lighting, etc.
- Physical labelling of the measurement/sampling points according with the code previously assigned.
- Conducting in situ non-destructive measurements in accordance with approved procedures.
- Sampling at specified points and of specified materials/waste following approved procedures.
- Sealing and repairing any areas affected by sampling, as required.

- Handling of samples following approved procedures ensuring that a chain of custody in maintained from the point of sample to analysis.
- Transport and storage of samples following approved procedures and transport regulations.
- Undertaking laboratory analysis using the agreed techniques and following approved procedures.
- Making and preserving characterisation records and reporting of the results.

The execution of characterisation activities should be supervised in order to ensure the correct performance of the works specification.

6.3. Executing characterisation work

No single characterisation technique will meet the needs of all situations. There are many considerations to be taken into account when designing a characterisation survey, such as the purpose, the waste and materials acceptance criteria, the desired accuracy, attributes of the area to be surveyed, the data to be collected, time, economic and personnel constraints, etc. These factors should be considered during the planning and initiation phases in order to produce the *characterisation plan*. In broad terms characterisation can use inferred, non-destructive; or destructive techniques (see Section 5.4 and Figure 5.2). Often a combination of approaches will provide the most efficient and effective approach.

Inferred characterisation: inferred characterisation techniques can be used in a range of circumstances. The following three techniques are probably used most frequently and are summarised in Figure 6.1:

> Computer codes can provide initial estimates of activation, however, measurement and sampling may be needed to validate results (CS-01, CS-02 and CS-03; see Table C.1).

- Radionuclide inventories and activity concentrations of activation products in a representative volume of material can be estimated through theoretical calculations based on geometry, material composition and a knowledge of the neutron flux that materials have been exposed to. Several computer codes are available to undertake such calculations. Monitoring, sampling and analysis of the activated materials are generally necessary to support validation of the computer codes used to perform the calculations. These estimations should be compared with direct measurements as decommissioning progresses and activated materials (e.g. reactor internals, reactor pressure vessels, and biological shield) become accessible for sampling. This technique can only be used for activation products, which should only be present where materials have been exposed to neutron fluxes primarily within, or in close proximity, to a nuclear reactor. It should be noted that that activation process can continue in the waste by minor neutron generation which can also be evaluated with computation codes. Spontaneous fission reactions in vitrified high activity waste is an example where the radionuclide inventory may continue to evolve by activation processes.

- Inventories and concentrations for hard-to-measure contaminants can be inferred by direct measurements of easy-to-measure contaminants scaled using a known mathematical relationship between the easy and hard-to-measure contaminants. This technique can be used for radiological and non-radiological contaminants (e.g. heavy metals, volatile organic compounds) where sufficient direct measurements (typically undertaken through sampling and destructive analysis) are available to establish a statistically valid relationship between the easy and hard-to-measure contaminants. Such scaling factors can be a simple ratio where the relationship is linear but may be defined through more complex mathematical equations, particularly where the relationship is non-linear. The scaling factors calculations must be supported by specific samples of the materials involved. Published generic scaling factors should only be used with extreme caution, and with an understanding of their limitations, but they can be useful particularly for qualitative purposes. This approach can be developed to define relationships for the range of contaminants producing a vector [1] (or fingerprint). In the case of radionuclides, Co-60 and/or Cs-137 are typically used as the key radionuclides that are easily measured using gamma spectrometry. The use of multiple key radionuclides allows continual checking that the associated scaling factors and the overall radionuclide vector remains valid. This scaling factor approach can be used for radionuclides present because of activation and/or contamination. However, great caution is required to ensure that approach remains valid. This is because the composition of contaminants can change significantly with respect to time, space and materials.

Well-founded isotopic vectors can reduce the need for extensive sampling campaigns and thus reduce costs.

Co-60 and Cs-137 are the preferred key radionuclides used in radionuclide vectors. However, Am-241 and U-235 can be used to a lesser extent.

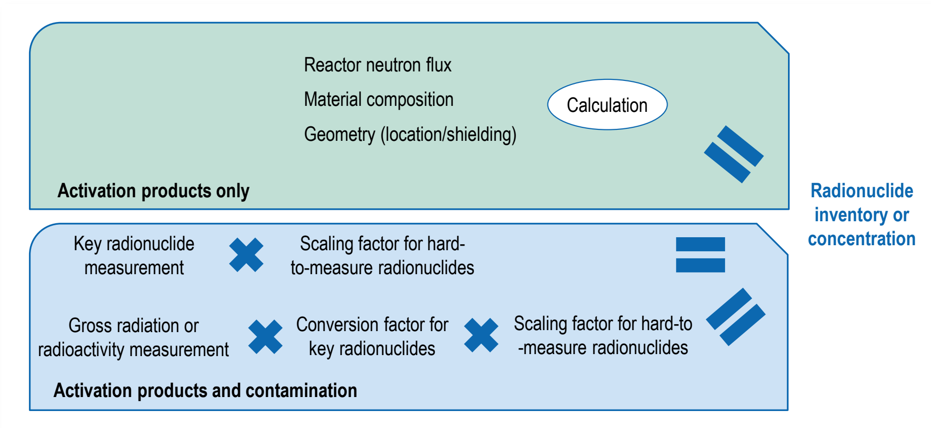
Scaling factor can be validated using the Co-60: Am-241 correlation (CS-09; see Table C.1).

- Finally the presence, inventory and concentrations of a key radionuclide can be inferred by direct gross measurement of radiation (for example using gamma dose rate measurements, gamma cameras, radiation probes, total alpha and total beta radioactivity measurements) multiplied by a conversion factor. The conversion factor can be established through modelling and/or sampling and detailed destructive analysis. Hard-to-measure radionuclides can then also be inferred using the scaling factor approach which is described above. It is extremely important to note that this method is not radionuclide specific and can be prone to significant interference from the presence of other radionuclides and high background radiation leading to

1. List of contaminants present together with its concentration relative to all contaminants. For radionuclides this means 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%.

positive bias and potential overestimation of activity. As the availability of radionuclide specific measurement techniques (e.g. high resolution gamma spectrometry) has become more widespread and affordable, the use of this particular technique is diminishing.

Figure 6.1: Inferred characterisation techniques



Non-destructive characterisation: A wider range of non-destructive characterisation techniques are available and in most circumstances these are deployed to make measurements of materials or waste in situ rather than within a laboratory.

Non-destructive radiological characterisation techniques include: gamma and alpha (Mahe, 2011) cameras (which can map the intensity of radiation); alpha, beta and gamma radiation meters (which provide discrete gross radiation measurements at individual locations; and radionuclide specific radiation detectors (which generally give multiple measurements covering radiation emitted with different energy levels or a single radiation measurement within a specific band or window of energy levels). The techniques employed will depend on the type of activation products or contamination present and the history of the facility. For example, the techniques employed in an area of high gamma dose rate will be different from those used for an area contaminated with natural uranium and daughter products or a plutonium contaminated facility. All of these techniques can be used to measure the intensity and map the distribution of activation products or contamination within materials in situ (for example across a nuclear facility) or within waste generated from decommissioning activities. A summary of the techniques in common use is given in Table 6.1.

> Measuring uranium and daughter products is difficult, particularly in an environment with abundant uranium background levels. Experienced staff are therefore necessary. (CS-07; see Table C.1)

Table 6.1: A summary of non-destructive radiological characterisation techniques for materials and waste

Gamma measurement methods	Detection	Application
Dose rate meters Use of teleprobes for inaccessible or high radiation levels.	Does not specifically quantify individual radionuclides.	Supports identification of radiation hazards, access limitations and development of decommissioning plans. Supports estimate waste volumes and waste sentencing. Useful for a very stable nuclide vector. Simplest of all gamma measurements and a very fast process.
Gross gamma counting Uses large scintillation detectors (e.g. plastic or NaI).	It is not nuclide specific.	Useful for very stable nuclide vectors. Can be very sensitive with large detectors; much more than dose rate measurement. Can be a very fast process. For reducing the impact of surrounding radioactive sources, the detector is inserted into shielding. Useful for clearance measurements in a shielded box in 4π-geometry.
Gamma spectroscopy Consists of: scintillators (NaI(Tl), CsI (Tl), $LaBr_3$(Ce), CdZnTe) or semiconductors (HpGe) detectors, shielding, electronic-unit, analogic to digital converter, multichannel analyser and evaluation unit (PC and acquisition software).	Specific for individual gamma nuclides and can quantify each gamma emitter depending on the energy resolution of the specific detectors. For each geometry of the measurement, an efficiency calibration should be performed.	Energy resolution determines how clearly different nuclides can be resolved from each other. Higher energy resolution detectors required when nuclide vectors are complex, and many gammas of close energies are emitted. Detection and intensity of gamma contamination by radionuclide. Used extensively in radiological clearance and waste sentencing processes.
Gamma tomography	Specific for individual gamma nuclides and can quantify each gamma emitter.	Potentially the most accurate technique; it corrects in three dimensions. Very powerful and no longer limited by computer processing time.
Gamma imaging (gamma camera) Monitors composed of an optical part (collimator, pinhole and coded mask), detector (scintillators) and acquisition software. Some systems incorporate spectroscopy.	Indication of the shape and location of the main radioactive sources, including the detection of hot spots.	Scans an area and overlays visual camera image with a survey of dose rate. Not usually used as final quantitative survey; uncertainties can be large when surveying a large area at a significant distance. Extensive experience from the nuclear medicine field.

Table 6.1: A summary of non-destructive radiological characterisation techniques for materials and waste *(cont'd)*

Neutron measurement methods		Detection	Application
Passive techniques	**Passive total counting**	Every neutron emitted is counted. Not specific to any individual actinide.	Can be very sensitive because of statistical precision, but easily upset by interference from other neutron emitters.
Passive techniques	**Passive coincidence counting (PNCC)**	Specific to actinides that decay by spontaneous fission.	If fissile material (or more appropriately, the fissionable isotopes of fissile species) is of interest, then interference from other spontaneous fission isotopes (e.g. Cf or Cm) is possible. Most often used to assess plutonium content by direct measurement of Pu-240 and inferred Pu-239 content by prior knowledge of the isotopic ratio.
Active techniques	**Active coincidence counting (ANCC)**	Useful for fissile isotopes, primarily U-235 and Pu-239.	An ever-present random neutron source induces prompt fission in fissile isotopes. Coincidence electronics rejects the random neutrons and only counts those from the fission.
Active techniques	**Cf-shuffler**	Useful for fissile isotopes, primarily U-235 and Pu-239.	A Cf-252 source is rapidly placed near the package and temporarily induces fission in fissile isotopes. The source is rapidly withdrawn and the delayed fission neutrons counted.
Active techniques	**Differential die-away (DDA)**	Determines the quantity of fissile material present. Potentially extremely sensitive. Only suitable for non-moderating materials.	A powerful neutron generator tube induces fission in fissile material with a burst of neutrons. The difference in time for the flux to decay back to normal for the package and an empty chamber determines the quantity of fissile material present.
Combined passive/active techniques		Where waste contains both uranium and plutonium, a combined active/passive method can be used to individually quantify each component.	The passive result indicates the Pu-240 and U-238 (if present in large quantity) and the active result indicates U-235 and Pu-239 content. Mathematical combination of the results combined with knowledge of the uranium enrichment and plutonium isotopic ratio allow for computation of the separate uranium and plutonium concentrations.
Gross alpha/beta counting Handheld and large area monitors composed of scintillators, gas-filled or semi-conductor detectors.		Not nuclide specific and measurement relative to calibration source.	Internal and external contamination of nuclear facility systems and surfaces can be determined from direct (in situ) measurements but because of radiation shielding effects results must be used with care. Can have use in gross characterisation of waste where the radiation is known to be homogeneous; where waste can be presented in a thin source (e.g. using a conveyor belt system); or to identify high concentrations particles in heterogeneous waste. Typically a fast process.
Alpha imaging (alpha camera)		Detects the ultraviolet radiation emitted by nitrogen following alpha radiation, including the detection of hot spots.	Scans an area and overlays visual camera image with a survey of alpha radiation levels. Not usually used as final quantitative survey; uncertainties can be large when surveying a large area at a significant distance. This is an emerging technology.

Source: Adapted from IAEA, 2007 and 1998.

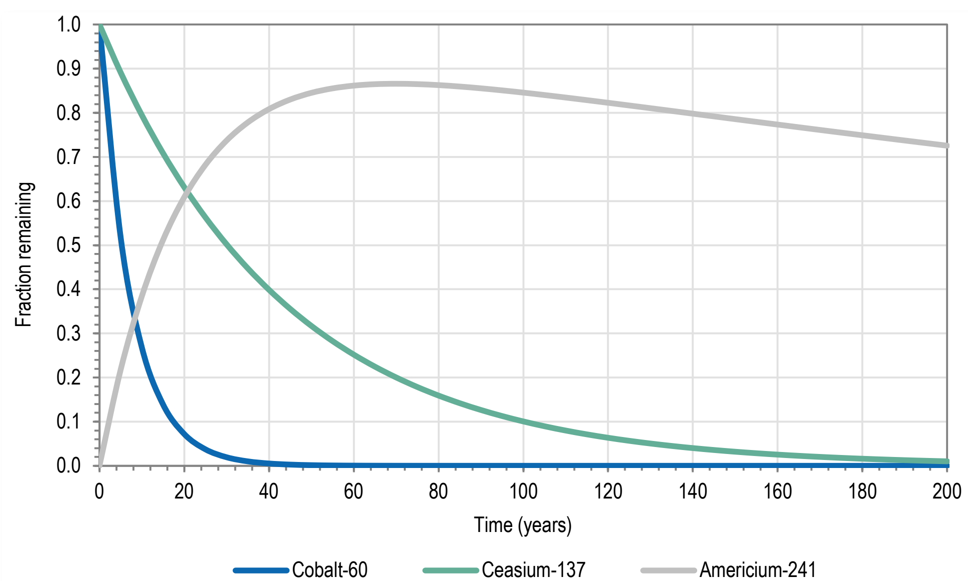
The timing of such characterisation can also be important. The main considerations include:

- It may also be necessary to delay characterisation of an area of low contamination until adjacent areas with higher contamination levels have been decommissioned and general background radiation levels decreased.
- An important key radionuclide (used with scaling factors), Co-60, has a relatively short half-life (five years) and delays to characterisation may preclude the use of Co-60 to infer difficult-to-measure radionuclides (Figure 6.2).

> Removal of contaminated structures reduces background measurements and allows characterisation of lower activity components (CS-13; see Table C.1).

- For plutonium contaminated facilities, delayed characterisation will allow the ingrowth of Am-241 and its potential use as a key radionuclide to infer difficult-to-measure radionuclides including isotopes of plutonium. However, this potential benefit needs to be offset against the detriments of deferred decommissioning, including exposing workers to higher gamma dose rates, associated with the Am-241 ingrowth as illustrated in Figure 6.2. It should be noted that this figure only shows the ingrowth of Am-241 but it is possible that Am-241 may be present in alpha contaminated facilities as an activation product rather than as a result of ingrowth.

Figure 6.2: Decay and ingrowth of commonly used radionuclides as a basis for scaling factors



Non-destructive characterisation also includes the measurement of non-radiological contaminants such as gases using gas sensors, as well as techniques to measure other physical (e.g. temperature; physical dimensions), chemical (e.g. pH) and biological properties (e.g. optical biofilm sensors). Increasingly some of these techniques, such as geographical positioning systems and techniques that map the layout of nuclear facility (e.g. use of scanning lasers), are deployed in tandem with non-destructive radiological measurements (e.g. gamma imaging systems) to build up three-dimensional images which characterise the distribution of contamination and/or activation products.

A significant limitation of non-destructive techniques is that they generally measure properties at the surface of materials or waste, therefore care is needed to ensure that subsurface properties, including contamination, which may be shielded from detection are not missed. For radiological measurements, this is less of a concern for energetic and penetrating gamma radiation but can be a significant matter for less penetrating radiation such as weak beta emitters and alpha emitters. These limitations can be partially addressed. Solutions include:

- the remote deployment of non-destructive radiological techniques, for example using pipe crawlers, allowing characterisation of normally inaccessible areas:
- for waste packages, averaging multiple measurements across the surfaces of the waste package, using multiple arrays of detectors or using turntables to rotate the waste package surface exposure to a detector.

However, typically the use of intrusive sampling and destructive analysis is required to give a full picture.

Sampling: Sample collection procedures are concerned mainly with ensuring that a sample is representative and is large enough to provide sufficient material to achieve the desired analytical detection limits. Sampling equipment can include a range of tools (e.g. chisels, pliers, hammers, drills, saws, sanders, corers, chemical stripping, laser ablation etc.) depending on the material or waste being sampled. Some key considerations are:

- Ensuring the sampling equipment is fully cleaned between sampling to avoid cross-contamination of samples.
- Ensuring the sampling technique does not interfere with the properties of the material or waste being characterised. A particular issue for radiological characterisation is to guard against the loss of volatile radionuclides which may be present. For example, tritium can be sampled using smears but drilling techniques generate heat and are likely to lead to tritium losses in bulk samples. This can be overcome by cold cutting techniques and pre-treatment of samples prior to analysis by the soaking of samples to leach out the tritium or by using of a high temperature furnace to drive off and capture the tritium.

Development of sampling method based on nuclide composition and need (CS-08; see Table C.1).

Sample collection is also likely to be required for non-radiological hazardous contaminants such as polychlorinated biphenyls (PCBs), asbestos or heavy metals. As discussed above, the planning phase should seek to optimise the characterisation work and there may be the opportunity to take combined samples for radiological and hazardous substances characterisation. However, it is important that all potential hazards are considered and assessed prior to sampling and analysis in order to protect the sampling technicians and the analysts.

All samples should be properly packaged and labelled at the time of collection and appropriately stored to ensure their properties are preserved up to the time analysis take place. The primary concerns are:

- the possibility of spills, leaks or breakage of the sample containers during handling, storage and transport threatening the safety of people and the environment;
- the loss of contaminants within sample;
- the potential for cross-contamination.

All legal requirements, including those covering the transport of materials and the management of any waste arising from the sampling process should be addressed.

Ensuring sample integrity is important for worker safety, environmental protection, as well as to limit the need for additional sampling.

Documentation of changes in the custody of a sample is important and tracking samples from collection to receipt at the analytical laboratory is normally done through a chain of custody procedure. There should be sufficient evidence to demonstrate that the integrity of the sample is not compromised from the time it is collected to the time it is analysed. Written procedures should be developed to cover the whole of the sampling process, from the field operations to the interface between the field operations and the analytical laboratory. The training and supervision of sampling technicians is also a vital process which is all too often forgotten or given too little attention.

Destructive characterisation: Destructive analysis is usually undertaken in a laboratory. However, not all laboratory techniques are destructive. For example, laboratory gamma spectrometry is often undertaken without substantially altering the nature of material or waste and consequently there is the potential to reuse (with careful consideration) such samples for further analysis. Laboratory techniques are generally more expensive and slower than in situ (non-destructive) methods, and because of the relatively small sample sizes analysed it is crucial that representative samples are obtained (Table 6.2). Destructive analysis also generally results in the generation of secondary radioactive waste which has to be managed. These strong drivers have led to the wider spread use of inferred and non-destructive (in situ) characterisation techniques. However, destructive analysis in a laboratory is likely to provide lower detection limits, more precise radionuclide measurements and can reveal subsurface properties of material or waste which are not seen when using non-destructive techniques. Consequently, destructive analysis often forms a key aspect of characterisation allowing the development of scaling factors (and radionuclide vectors) which underpins the wider use of inferred and non-destructive techniques.

Table 6.2: A summary comparison of non-destructive and destructive radiological characterisation techniques

Parameter	Non-destructive	Destructive
Cost	Low-medium	Medium-high
Resolution of radiological content	Low-medium	High
Measurement time	Quick (up to 1 000 s measurements/hour)	Slow (few measurements/day)
Detection limits	Medium-high	Low
Ability to give large areas/volume	Good	Needs care as small sample size may give very localised results, reflecting the sampling location but not the wider (and more general) environment activity concentrations
Ability to measure subsurface distribution of contamination	Low	High

Destructive analysis typically involves sample destruction using strong acids, oxidising agents and/or high temperature treatment. This generally results in the contaminants of interested being in a liquid form. Chemical separation processes can then be used to purify the required element or compound, which can then be analysed. For radiological characterisation typically the element of interest is prepared into a sample (e.g. for alpha spectrometry evaporated or electroplated on to steel discs) which can then be presented to a radiation detection in a standard fixed geometry of known counting efficiency. The techniques in common use are summarised in Table 6.3.

The selection and proper use of appropriate instruments for both direct measurements and laboratory analysis are critical factors in assuring that the characterisation activities accurately determine the radiological status of materials or waste, and these should have been considered in the planning and initiation phase and specified in the *characterisation plan*. The driving issues in instrument selection are the type of measurement data required (e.g. surface activity, radiation gamma level, activity concentrations etc.), the nature of the contaminants being assessed and the sensitivity of the instrument. The measurements/sampling activities should only be performed by trained individuals and in accordance with approved written procedures and properly calibrated instruments that are sensitive to the suspected contaminants. All the relevant aspects related to safety and radiation protection should also be specified in the written procedures.

Destructive characterisation also includes the measurement of non-radiological contaminants including physical; chemical and biological parameters which may be required to meet a range of characterisation objectives associated with decommissioning and waste management, including the protection of workers. Physical measurements may include aspects such as the shear stress of sludges or the grain size of solid materials. Destructive analysis may be used to determine a wide range of chemical characteristics, typically including asbestos, metals and organic substances. The presence of asbestos in an aged facility is often a key concern. Its location and form should be identified in order to safeguard personnel and to manage its safe removal without cross contaminating the bulk demolition waste. Heavy metals such as lead may be found in paint coatings, and the presence of copper, chromium and arsenic may indicate the presence of chromated copper arsenate, a wood preservative historically used in wet systems such as cooling towers. The use of vectors or fingerprints can also be applied to chemical contaminants. For example, the measurement of Benzo (a) pyrene (BaP), a polynuclear hydrocarbon, can be used to infer the concentration of coal tar, often found in roof felt and other waterproof barriers that can render the waste as hazardous. Biological determinants may be needed to support a range of characterisation objectives. For example testing for the presence of legionella in wet systems and E-coli in sewage systems may be needed to ensure worker safety, while understanding the organic content of waste may be important to ensure waste interim storage and disposal requirements can be met.

Table 6.3: A summary of destructive radiological characterisation techniques

Radiation types	Radionuclides	Preparation method	Final measurement
Alpha emitters	Po-210, Ra-224, Ra-226, Th-230, Th-232, U-234, U-235, U-236, U-238, Np-237, Pu-238, Pu-239, Pu-240, Am-241, Cm-242, Cm-244, Cf-252	Acid digestion/oxidation/ leaching followed by: precipitation, solvent extraction, ion exchange chromatography, extraction chromatography	Gross alpha counting Alpha spectrometry
Beta emitters	Ca-41, Ca-45, Fe-55, Ni-63, Sr-89, Sr-90, Tc-99, I-129, Pm-147, Pu-241	Acid digestion/oxidation/ leaching followed by: precipitation, solvent extraction, ion exchange chromatography, extraction chromatography	Gross beta counting Liquid scintillation counting
Volatile Beta emitters	H-3, C-14	Distillation, leaching, decomposition and gas capture	Gross beta counting Liquid scintillation counting
Gamma emitter	Co-60, Ru-106, Cs-134, Cs-137, Eu-152, Eu-154, Eu-155, Am-241	Drying, grinding and evaporation	Low and high resolution Gamma spectrometry
Non-radiometric	C-14, Tc-99, I-129, Np-237, uranium, thorium and plutonium isotopes	Acid digestion/oxidation/ leaching	Fluorimetry Mass spectrometry (ICPMS, TIMS, SIMS, RIMS and AMS)

AMS – accelerator mass spectrometry; ICPMS – inductively coupled plasma mass spectrometry; RIMS – resonance ionisation mass spectrometry; SIMS – secondary ion mass spectrometry; TIMS – thermal ionisation mass spectrometry.

6.4. Characterisation data records

Characterisation work generates a large amount of data and *characterisation records,* which need to be retained for a defined period (often many years) in order that the characterisation results are traceable back to specific samples or measurement locations and the quality of the results is understood. Retaining raw characterisation data, such as gamma spectrums, allows for the reinterpretation of characterisation results, in situations where the original results are questioned or new information come to light. The quantity of information involved and the need for traceability present a significant data storage challenge. Modern systems are increasingly allowing the electronic capture of characterisation data at source and the automatic transfer of such information to all parties who will use or need access to the data. For example, monitoring or sampling data captured on-site can be automatically transferred to a laboratory and in turn laboratory analytical results can be automatically transferred for geo-statistical analysis. Wherever practicable quality assured electronic transfer of characterisation data and records should be used. This is because manual transcription of such information inevitably introduces errors.

To address data management, a system should be developed through procedures covering the making, maintaining, storing and retrieving of characterisation data and records. An important consideration is to establish a unique codification system to cover structures, systems, components, waste packages, measurement locations, sampling points and analysis allowing characterisation data/records to be traceable. Based on these criteria, a code for each measurement, sample and analysis can be assigned before the activities are executed. Such systems should also ensure that other important information can be easily retrieved when required. This includes: the dates of measurements, sampling and analysis; the technician who undertook the work; and any significant deviations from approved procedures are traceable. Electronic database systems are now almost universally used to manage this type of information. Particular attention should be given to ensuring that such systems are fully backed-up in a separate location and preserved in a retrieval form.

> Characterisation records are best held on a centralised electronic system. Duplication in a different form and place ensures preservation.

The *characterisation records* are the main output from the implementation phase and these should contain details of all activities undertaken. They should include the description of the field activities including in situ measurements and diagrams identifying sampling and measurement locations and sample types. In addition, they should record the measurement results including the detection limits, standard deviations, analytical procedures and sample and analytical codes assigned in the field and at the laboratory within the chain of custody documentation. Any problems with sampling/measurements and subsequent analysis should also be documented and a decision on whether the results are valid should be recorded. This information can sometimes be contained within a *supervision activity report*.

Any organisation collecting and evaluating characterisation data must be concerned with the quality of results. The organisation must have results that meet a well-defined need, use or purpose and comply with programme requirements. To meet the objective, the organisation should control the technical, administrative and human factors affecting the quality of results. The characterisation report should contain sufficient details of the quality control and quality assurance (QC/QA) measures, or signpost relevant information, so that the quality of the characterisation results can be understood. QC/QA measures are set out in ISO17025 and some of the main aspects are described below:

- ***Calibration and quality control of equipment:*** Instruments, devices and test equipment used for measuring radioactivity should be commissioned, operated, calibrated, checked and maintained to ensure that analytical specifications are met. These processes are carried out in adherence to any applicable standards and methods and as specified in the laboratory's quality manual and standard operating procedures and in accordance with the manufacturer's instructions. Instrument configurations during calibration should match those used for subsequent analytical measurements of samples. Suitable calibration procedures are an essential prerequisite for providing confidence in measurements made to demonstrate compliance with acceptance criteria. In the interval between calibrations, the instrument should receive a performance check prior to use and periodically during use. Instrument response, including both the background and check source response of the instrument, should be tested and recorded at a frequency that ensures the data collected with the equipment is reliable. For most portable radiation survey equipment, it is recommended that a response check be performed daily when in use. Extremes temperatures can cause drift in instrument calibrations and some components can be fragile and sensitive to shocks of puncturing (e.g. the films on the face of radiation monitoring detectors). If the instrument response does not fall within the established range, the instrument must be removed from use until the reason for the deviation can be resolved and acceptable response demonstrated. If the instrument fails the post-survey source check, all data collected during that time period with the instrument must be carefully reviewed.

- ***In situ measurement and samples:*** Duplicate in situ non-destructive measurements and the taking of duplicate samples for destructive analysis should be part of the quality control requirements. This aspect can be missed, particularly when destructive analysis is contracted out, because of the assumption that the quality control aspects will be covered by the contract laboratory. The number of quality control in situ measurements and samples (which are submitted for analysis) is determined by the available resources and the degree to which assurance is needed. This number is determined on a case-by-case basis during the planning phase and it includes repeated measurements and field replicate samples (i.e. a single sample that is collected, homogenised and split into equivalent fractions in the field).

Duplication of in situ measurements and analyses by a second laboratory should be conducted for approximately 5% of measurements and analyses.

- ***Laboratory samples and analysis:*** The use of quality control samples should be an integral element of a laboratory quality assurance programme. The laboratory should have as part of the normal operational sample load the following quality control samples: blank, matrix spike, laboratory control sample and laboratory duplicate. Quality control sample results should be tracked, trended, and compared with predetermined ranges of acceptable performance to identify conditions that are in, or may lead to, non-conformance with programme specifications. Such conditions should be tracked through the corrective action programme.
- ***Performance evaluation programme (inter-laboratory comparison):*** Participation in external performance evaluation programmes is an important independent check on the accuracy, possible bias and precision of the analytical methods used. While, the availability of inter-laboratory exercise or suitable certified reference materials can be a limitation, internal or contracted radio-analytical laboratories used for the characterisation should participate in such programmes. External performance evaluation of in situ measurements is much rarer but should be undertaken where/when available. Opportunities to benchmark activation computation codes should also be taken.

6.5. References

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Chapter 7. Characterisation assessment and evaluation

The ultimate aim of characterisation is to meet the objectives of the project through the collection of data generated from relevant historical information, calculation, measurement, sampling and modelling activities. The quality of data is therefore a measure of its adequacy to allow decisions to be made in line with the project objectives. Data assessment is undertaken on individual results, through the adherence to *quality plans*, as well as on whole data sets, considering the relationship between individual results to identify outliers etc. Therefore there is a need to ensure the validity, consistency and consolidation of the whole dataset. Learning from earlier characterisation campaigns, operations, existing inventories, etc. is also of crucial importance. This increases the likelihood that sufficient characterisation information will be obtained and that sufficient samples have been taken and retained by the laboratory for any necessary additional or repeat analysis.

The characterisation assessment process is summarised in Figure 7.1 and begins with data verification and validation. Once sufficient, or all the characterisation data is verified and validated a systematic data assessment process can commence.

A systematic characterisation assessment process is likely to use the elements defined in the data quality assessment (DQA) methodology (EPA, 2006). This involves the scientific and statistical evaluation of characterisation data to determine if it is of the right type, quality and quantity to support meeting the characterisation objectives and supporting associated decision-making (Figure 7.1).

The DQA process, as illustrated in Figure 7.1, involves five steps:

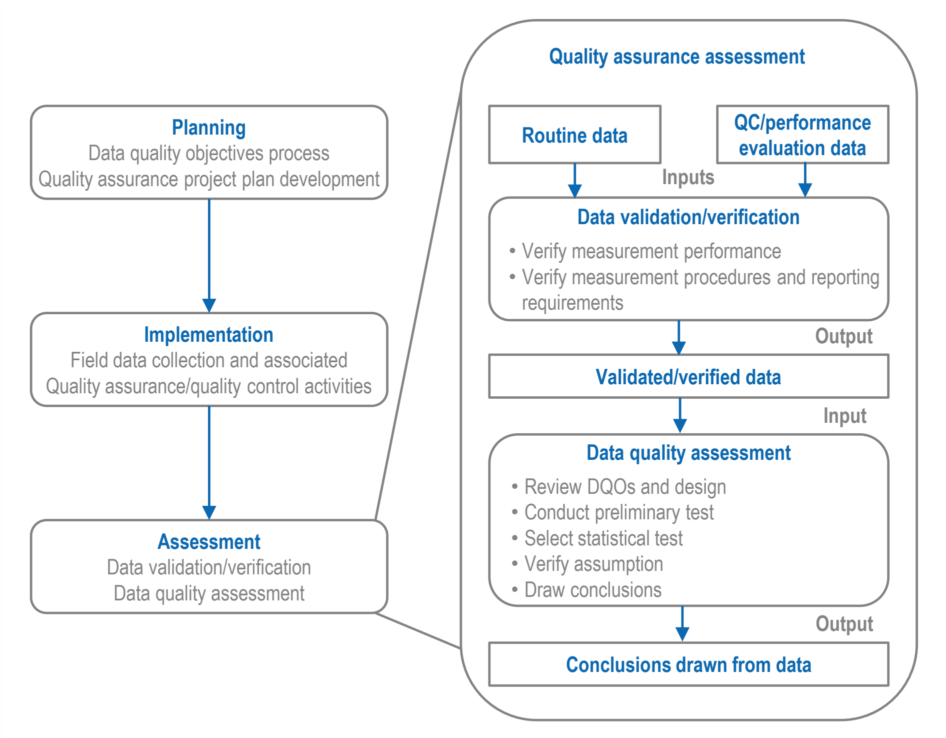
- review of characterisation objectives and data collection design;
- conduct a preliminary data review;
- data evaluation techniques;
- verification of assumptions and uncertainty quantification;
- drawing conclusions from the data.

By following the DQA process, any deficiencies or gaps in data can be identified and captured via an amended characterisation plan (CS-04; see Table C.1).

This is an iterative process and the outcomes from each step may require the *characterisation plan* to be amended if it is found that it is inconsistent with the project objectives, similarly for the outcomes from the statistical tests.

The following sections describe the main elements of the data assessment process.

Figure 7.1: Data assessment and evaluation throughout the project life cycle



QC – Quality control; DQO – Data quality objectives.
Source: EPA, 2006.

7.1. Data verification and validation

It is important that the data is collected, recorded and transferred according to a *quality plan* which would ideally be specified as part of the *operating procedure*. The quality of the data collected depends on the equipment and methods used. This will include adequate checking and calibration of all equipment used, clear operating instructions for both equipment and techniques and suitable training of all workers involved. Any deficiencies or problems that occur during the implementation phase, such as with equipment, measurements or sampling, should be documented and reported, ideally in *characterisation records*.

Data verification and validation are techniques used to accept, reject or qualify data in a consistent manner, it is only after these steps have been completed that data evaluation should be carried out.

Data verification ensures that the requirements stated in the documents (e.g. *operating procedures* and sampling plans) are implemented as prescribed. Verification activities will include:

- audits to confirm that all activities have been carried out in accordance with the *operating procedures*;
- checks to ensure data has been transcribed accurately;
- recording and tracking of performance of measurement and sampling equipment;
- independent audit of documents, data and equipment.

The process of the data validation ensures that the characterisation results meet the criteria defined during the initiation and planning phases or any necessary modifications are justified and will still support the characterisation objectives being met. This process consists of the following steps:

- Validation that the data meets the defined descriptors within the characterisation plan. For example, number of measurements/analysis, correct determinants, correct minimum detectable concentrations and level of uncertainty in measurements obtained.
- Qualification of data whether it is acceptable or not acceptable. This involves looking for outliers, errors, and inconsistency and should be undertaken considering historical information. It is important to have an open mind as suspected inconsistencies can also result from limitations in understanding with the data being valid.
- Ensuring corrective actions have been taken where necessary, for example recalibrations or substitution of faulty equipment.

The data verification and validation processes should be conducted by expert and experienced staff, who are likely to identify weaknesses and errors in the data. These can include laboratory, measurement, quality assurance and independent experts preferably with a good knowledge of the characterisation process and an understanding of the context of the characterisation project. It can be useful to summarise the overall findings of this process in a *data verification and validation report* and these steps should be covered by a *characterisation quality plan*. Once the data quality has been established through verification and validation the data assessment process can be undertaken.

> Laboratory, measurement, quality assurance and independent experts are seen as most important to the data verification and validation process.

7.2. Review of objectives and data collection design

Before assessing the characterisation data, the characterisation plan, in particular the characterisation objectives and the data collection design should be reviewed. This step will provide assurance that the original objectives are valid and allow the data collection activities to be appraised for consistency with these objectives. It can be useful at this stage to translate the objectives into statistical hypothesis which can be tested at a later stage in the process. At this stage uncertainty limits (commonly set around 95% confidence levels) can also be established which depend on the appetite for risk. In practice the appetite for risk will depend on the decision the statistical hypothesis is supporting. For example, the accepted level of risk may be very low for a decision associated with the free release of materials and waste whereas for estimates for the waste volumes arising from decommissioning the acceptable level of risk may be significantly higher.

Another important aspect to consider at this stage is the data collection design. If the data collection design has been judgemental great care need to be used in the assessment and interpretation of the results. Strictly speaking judgemental design will have been undertaken using judgement about what data will meet the stated characterisation objectives and consequently the wider use of such data should be very carefully considered. However, judgemental sampling can be very useful to target answering specific characterisation objectives, for example the identification of a source of contamination. Probability design, where data is collected on a randomised basis generally allows for great flexibility in the way in which characterisation data can be assessed and used.

7.3. Preliminary data assessment and review

In the planning phase (Chapter 5) the requirements of the characterisation activities should be specified in the *characterisation plan*. This will outline when, where and how many measurements/samples should be collected to adequately inform the project objectives. It should also set out in high level terms how the characterisation data will be assessed. This plan would then be followed in the implementation phase (Chapter 6) during which the characterisation data is collected and the *characterisation records* made.

A preliminary assessment of characterisation data should be undertaken in a timely fashion, ideally as soon as possible during the implementation phase when the initial characterisation data are received and prior to data being transcribed into any data assessment tool. 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. Such an assessment is usually performed to ensure that an adequate data set is available for future decision-making. This reduces the likelihood that rework or reanalysis 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 measurement team/laboratory at the earliest possible opportunity. This should enable rapid resolution of the issue as well as providing information to enable trending and performance tracking of the individual analytical techniques.

> Timely assessment of data will ensure any problems can be rectified early, limiting the likelihood of rework in later project phases.

Initially, the preliminary data assessment involves review of relevant quality assurance reports, paying particular attention to apparent anomalies in recorded data, missing values, deviations from standard operating procedures, and the use of nonstandard data collection techniques. These should have been captured by the data verification and validation and should be summarised in the characterisation verification and validation report if one has been produced.

Following this a range of statistical techniques and graphical representations can be used to analyse the characterisation data to identify any patterns or relationships.

Statistical techniques that can be used to understand the statistical nature of the characterisation data include the uniformity, dispersion and correlation between variables. This includes the mean, median, mode, variance, standard deviation, percentile distribution and correlation tests (such as Pearson's and Rank Spearman's correlation coefficients). Graphical representation, for example using frequency histograms and Box and Whisker plots, can be used to understand the distribution of the data – for example whether it is normally distributed or skewed. The correlation of variables can be investigated through scatter plots. It is important to examine the data in this way prior to the subsequent evaluation in order that any assumptions and limitations are established. For example, statistical measures such as the variance and standard deviation are only meaningful for normally distributed data. If the data has a skewed distribution, for example a lognormal distribution, then care is need in the transformation of data and the use of associated statistical tests.

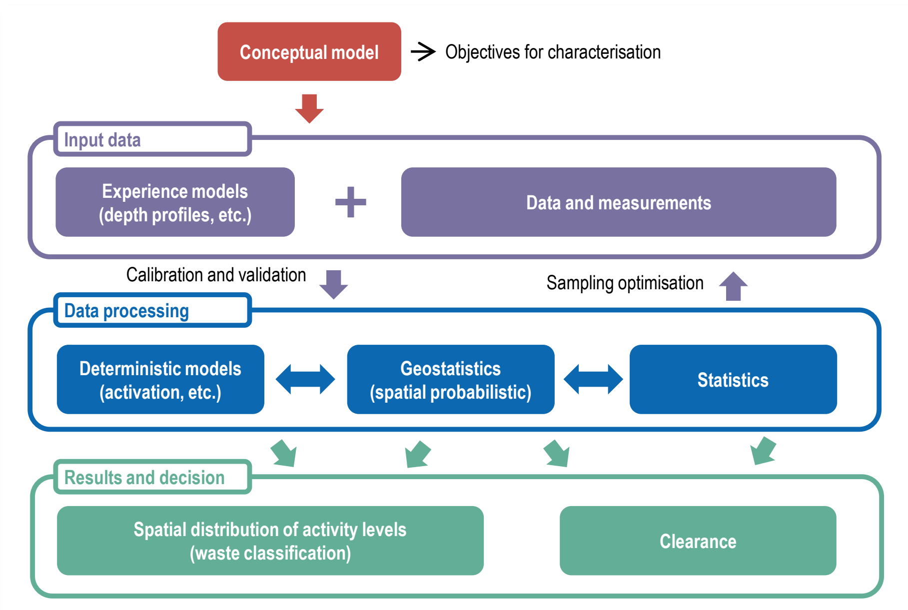
7.4. Data evaluation techniques

The preceding stages provide assurance that the data collected through characterisation activities are suitable for processing and evaluation to inform the project objectives. The processing and evaluation techniques selected will depend on the final use of the data, for example for waste routing or mapping of the spread of contamination. The underlying assumptions must be identified which must hold for the statistical procedures to be valid. There are several commonly employed techniques:

- **Statistical techniques** include significance testing, outlier tests and calculation of mean at an appropriate confidence level (e.g. typically the 95% confidence level). The specific technique employed and confidence level employed will be dependent on the appetite for risk (probability of taking the wrong decision) and statistical properties (assumptions) of the data. Important statistical assumptions are whether the data is normally distribution or not; for variables whether the data sets are independent or paired; whether a data set is being compared to a fixed threshold or another variable value. For example, in the last case a one sided statistical test could be used to compare the activity concentration of man-made radionuclide with a fixed regulatory value (e.g. a clearance level), however in the case of naturally occurring radionuclides, there is a variable natural background which may mean that two sided statistical tests would be more appropriate.

- **Numerical modelling approaches** are used to describe the behaviour and distribution of radioactivity, for example activation distribution, diffusion, migration, flow and transport. In this case specialised modelling techniques will be required to ensure the uncertainty is understood and taken into account when evaluating the data.
- **Probabilistic spatial approaches** (such as geostatistics) are necessary when the distribution of contamination cannot be modelled deterministically. Geostatistics models the spatial distribution of activity levels by combining data from various types: documented information, in situ measurements and sample analysis of samples as illustrated in Figure 7.2.

Figure 7.2: Illustration of the process of data evaluation



The use of GIS can make trending easier and the data more accessible to other stakeholders (CS-10; see Table C.1).

Use of graphical modelling for evaluation and presentation of results is largely adopted by owners and regulators. GIS-based software (geographic information system) as well as 3D viewer interface are the most commonly used tools to perform these tasks. Care is needed not to over interpret such visualisation which by their very nature are required to interpolate and extrapolate from the original characterisation data to provide a seamless image. However, these are very visual tools and provide an excellent means to convey the summarised findings from the evaluation of characterisation data. They are useful to facilitate data understanding and discussion about data and results in combination with more classical statistical techniques and charts.

In practice a range of the techniques described above are used and confidence is generated in the evaluation of characterisation data through this multi-layered data assessment process.

7.5. Verification of assumptions and uncertainty quantification

Once the data evaluation techniques of choice have been established it is important to verify the assumptions and validate the approaches used where practicable. This can involve undertaking further statistical tests on all the data, for example checking the assumption about the distribution of the data are correct. This may result in the need to use alternative statistical techniques. In most circumstances numerical modelling approaches and probabilistic spatial approaches can be validated through supplementary actual characterisation data. Where differences are identified then allowance can be made through calibration factors. However, all such adjustments should be fully justified and documented.

Uncertainty will arise as a result of the variability of contamination and activation products in the materials or waste being examined. Since it is impossible in every situation to measure the residual radioactivity at every point in space and time, the results will be incomplete to some degree. Uncertainty is also associated with measurement, sampling and analysis techniques, and includes random and systematic errors. Random errors affect the precision of the measurement system and present as variations among repeated measurements. Systematic errors in measurements are biased giving results that are consistently higher or lower than the true value. A knowledge of these errors combined with the use of statistical techniques allows overall compounded errors in characterisation results to be calculated. This information can be taken into account in particular when comparing these results to specific threshold value against which decisions will be made (see Section 5.6, Figure 5.2).

There will also be uncertainties associated with the data assessment (e.g. uncertainties resulting from modelling measurements) which should be identified and evaluated if possible. For example a confidence level can be established in modelled concentrations which have been interpolated or extrapolated from relationships established between the spatial variation in activity concentration.

At a macroscale verification is possible by comparing characterisation information for similar components from one facility to another one. For instance, comparing the activation results and measurements on primary circuit steel for a pressurised water reactor (PWR) to results obtained for other PWR reactors, with similar life cycle operating conditions. However, care must be taken to understand the limitations in such comparisons for example where the operational history is significantly different or has involved contamination events for example through fuel failures.

An understanding of the assumptions and uncertainties associated with characterisation information is crucial to making informed decisions based on such information. Such information allows risk informed decision-making.

Finally, it is worth noting that uncertainty and the data collection design are closely linked. Statistical and geo-statistical models can be applied to optimise the radiological characterisation effort by reducing the number of samples or measurements required to meet the data quality objectives (DQO). This sampling/measurement optimisation is directly linked to uncertainty performances (according to required or expected confidence interval for instance or acceptation criterion).

7.6. Drawing conclusions from the data

The final step is to apply the chosen data evaluation techniques to all of the characterisation data and draw out the conclusions. It is important to perform the calculations and document the methods used (including any computer software used) and results obtained. It is acceptable to remove recognised anomalies or outliers in data sets but this should be fully documented including the justification for doing so.

Depending on how the characterisation objectives have been framed the primary results are likely to answer specific questions based on the output from statistical tests, numerical modelling and/or probabilistic spatial approaches. For example, statistical tests combined with geo-statistical techniques maybe be used to estimate the quantities of different categories of waste that will be arise from decommissioning or statistical techniques may be used to define the categorisation of specific waste packages. When drawing such conclusions it is important to state the underlying assumptions and to provide a quantitative (and where not possible a qualitative) estimate of uncertainty even when it is not a specific requirement (for example for relevant waste acceptance criteria (WAC) for a treatment, storage, transport or disposal route). This information should remain linked to main outcomes from the characterisation work to ensure that decision are taken based on a clear understanding of risk. Characterisation reporting is covered in Chapter 8.

7.7. Reference

EPA (2006), "Data Quality Assessment: Statistical Methods for Practitioners", EPA, QA/G-9S.

Chapter 8. Characterisation reporting and review

The final phase in the characterisation process is reporting and review.

Through the characterisation process a number of activities are undertaken and a wide range of documentation is generated including plans, records and assessment reports. It is important to summarise the work that has been undertaken, the results obtained, what they mean and how they answer the characterisation objectives. It is good practice to draw all of this information together in a project *characterisation report*.

The *characterisation report* should be a standalone document that contains sufficient information to understand the evidence base upon which the characterisation objectives have been met. This is important as the characterisation objectives often relate to, and support, fundamental decisions such as how to decommission a facility or how to manage waste arisings.

It is recognised that in most cases (with the exception of very small characterisation projects) all the supporting documentation cannot be contained within the *characterisation report*. Therefore it is important to establish clear and accurate references to such evidence within the characterisation report and to ensure that this supporting documentation is retained and is easily accessible if needed.

In some case the final *characterisation report* will be required to meet regulatory requirements and therefore it is important to consider these when drafting the report.

An internal dedicated review process is essential to ensure that characterisation gives statistically robust and representative results. Review by external experts is also important, while benchmarking and networking are useful.

> An internal dedicated review process is essential to ensure that characterisation gives statistically robust and representative results.

Internal technical review of the characterisation report is essential to ensure that the characterisation process and the interpretation of what the results mean for the characterisation objectives and any associated decisions is robust. Review by external independent experts once the report is complete can also be very useful. A characterisation project review should also be undertaken connected to the drafting of the characterisation report. This should consider and summarise the learning from the characterisation to support the optimisation of future characterisation campaigns. This can be undertaken a systematic way considering the inception of the characterisation arising from the characterisation strategy (Chapter 2), the management arrangements (Chapter 3) and the sequential phases of the characterisation process (Chapters 4-8).

Finally, where the characterisation work has been conducted within the framework of a high-level *characterisation strategy* (Chapter 2), it is important to review whether the characterisation work has fulfilled the expected elements of the characterisation strategy and to record this within the characterisation report. It is also worth checking whether the characterisation work has meet some of the broader objectives of the *characterisation strategy*. This will support the future review of the *characterisation strategy* and ensure that over the long-term characterisation work is optimised.

Chapter 9. Conclusions and areas for future work

9.1. Conclusions

Radiological characterisation plays an important role in decommissioning of nuclear facilities and is central to the development, implementation and optimisation of decommissioning plans. Effective characterisation allows the extent and nature of contamination to be determined, providing crucial evidence to support facility dismantling, the management of material and waste arisings, protection of workers, the public, the environment, and associated cost estimations.

This report has explored the practical implementation of nuclear facility characterisation from a waste and materials end-state perspective, targeting characterisation practitioners in particular. It identifies international good practice and provides practical advice distilled from a questionnaire and international conference on this subject, and on case studies, and international standards and guidance. Information is presented through a systematic discussion of the characterisation process. A previously published companion report (NEA, 2013) provides strategic guidance for decision makers on the selection and tailoring of strategies for radiological characterisation and gives an overview of good practice for radiological characterisation at different phases of the life cycle of a nuclear facility.

There is evidence that a strategic life cycle approach to characterisation is now being adopted internationally. This takes into account multiple characterisation objectives across the life cycle of a facility and associated waste management, seeking to ensure the right information is available at the right time to support the development and implementation of decommissioning and waste management plans. Increasingly, guidance and practitioners are also recognising the opportunity to take an integrated holistic approach to characterisation, considering the optimum approach to providing the necessary radiological, physical, chemical and biological information.

In addition, there is considerable international consistency in the basic approach taken to radiological characterisation. An approach driven by characterisation objectives, with the similar basic process steps (e.g. initiation, planning, execution, evaluation and reporting), is almost universally established practice. Such an approach reflects the adoption of recognised high-level industry good practice international (IAEA, 2007) and national guidance (EPA, 2006), supplemented by more detailed international and national guidance covering the characterisation process and a range of specific characterisation techniques. The data quality objectives (DQO) methodology (EPA, 2006) in particular has been very influential in encouraging a systematic approach to characterisation work.

There is evidence that this consensus approach, through the development of international standards and guidance, is leading towards harmonisation and optimisation of radiological (and associated) characterisation internationally, both at a strategic and tactical level. However, evidence from the questionnaire, conference and case studies shows that characterisation remains a highly skilled and technical craft. At a high-level, national regulatory requirements share a common framework, while precise national requirements and the level of prescription of the approach vary significantly. In addition, the characterisation challenges and objectives can vary significantly. Consequently, characterisation work is continuing to require:

- customised solutions at a detailed level;
- highly skilled and experienced practitioners to plan, execute and evaluate characterisation work and ensure its quality;
- the use of multi-layered techniques, recognising their limitations, to provide the required level of overall confidence in final characterisation information;
- innovation to establish faster, cheaper, more accurate and representative techniques.

By compiling shared learning from experiences and summarising good practice, this report seeks to support the further optimisation and harmonisation of approaches to characterisation while providing detailed practical advice to support characterisation practitioners.

9.2. Further work

A comprehensive review of international research and development needs was undertaken in 2014 (NEA, 2014) and the phase 1 report (NEA, 2013) considered potential areas for further work. In summary, these highlighted the following potential areas for international collaboration:

- establishing learning from the most challenging characterisation situations, in particular where major nuclear events have occurred;
- developing an international approach and/or standards for statistical sampling (representativeness, grid density, defining an acceptable level of uncertainty);
- developing methods, hardware and modelling to develop characterisation of general mobile contamination intrusion into materials and along macro structures such as concrete cracks;
- extending technologies for rapid alpha and beta non-destructive measurements on structures before dismantling, especially for difficult-to-access structures;
- developing an international approach or standard for estimating the level of impurities in metals, graphite and concretes, especially for new reactors;

- exploring the optimisation of characterisation efforts in a plant life cycle perspective through an in-depth analysis of the interdependence between data obtained in life cycle phases.

As a result of the phase 2 work (documented in the present report) the following additional areas have been identified as having merit for further attention:

- Specific consideration of non-radiological characterisation in the nuclear setting. Cross learning from both non-radiological and radiological characterisation techniques could be considered and guidance could be provided on how to optimise non-radiological characterisation in the nuclear setting.
- The development of international reference materials would help to ensure the quality of characterisation results. This could include reference "*contaminated*" facilities to assess the accuracy and precision of in situ characterisation techniques, and reference samples (e.g. drums or containers) to assess the accuracy and precision of non-destructive and destructive (including) laboratory techniques.
- The development of performance indicators to assess the success of characterisation. This would need to explore measures to understand how successful characterisation work has been in meeting its stated characterisation objectives, while optimising associated resources (costs, time and people). A need also exists to consider the characterisation process itself and what impact it has on the optimisation of decommissioning and waste management.
- A review of the wide variation in retention times for samples and characterisation records across all categories of radioactive waste. The variation in views regarding the amount (percentage) of characterisation measurements or analyses that should be duplicated should also be examined. International guidance may be beneficial in this area.
- Further industrialisation and automation of characterisation process, taking advantage of new technology (in particular, in situ characterisation techniques) and experience, should help to lower cost and potentially improve quality.

9.3. References

EPA (2006), "Data Quality Assessment: Statistical Methods for Practitioners", EPA, QA/G-9S.

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

NEA (2014), *R&D and Innovation Needs for Decommissioning Nuclear Facilities*, OECD, Paris.

NEA (2013), "Radiological Characterisation for Decommissioning of Nuclear Installations", NEA/RWM/WPDD(2013)2, www.oecd-nea.org/rwm/docs/2013/rwm-wpdd2013-2.pdf.

Annex A: Questionnaire

A questionnaire structured around a life cycle approach to characterisation (NEA, 2013) and the use of systematic planning approaches such as data quality objectives methodology (EPA, 2006) was developed. It was recognised at an early stage that there are significant differences in the roles of the regulators and owners and consequently two versions of the questionnaire were used to target the collection of views. It was also appreciated that aspects of radiological characterisation may change significantly prior to and during facility dismantling. This is because during facility dismantling the role of characterisation may transition towards surveillance to support materials and waste sentencing. Consequently some questions were designed to explore the responders' views of characterisation good practice prior to and during dismantling.

The questionnaires were sent to a broad range of international characterisation experts who were able to draw upon practical experience in radiological characterisation of materials and waste. The experts were identified primarily through the national representatives in the Task Group on Radiological Characterisation and Decommissioning within the NEA Working Party on Decommissioning and Dismantling and their supporting national networks.

Fifty-three survey responses from characterisation experts from thirteen countries, including ten European countries, Canada, Japan and the United States were received. Both the regulators and owners responding to the questionnaire had a broad experience across the nuclear industry; with the regulators' experience generally being marginally broader. Overall the average responder's experience of radiological characterisation was around 15 years. The collective experience of those responding to the regulator questionnaire was approximately 300 years and for those responding to owner questionnaire the collective experience was around 500 years.

A detailed and systematic evaluation of the responses to the questionnaire was undertaken by the task group (NEA, 2016). This was followed by a consultation process regarding the key learning points, with the original questionnaire responders and other interested experts identified through international conferences (PREDEC, 2016 and WM Symposia, 2016). Taking account of the consultation process, the key learning points are summarised below, covering the national context in which characterisation takes place followed by the systematic characterisation process involving initiation, planning, implementation, evaluation and quality assurance.

National context

- Immediate dismantling is the preferred decommissioning strategy, over deferred decommissioning, but recognising that it may not always be practicable.
- Interim waste storage facilities are available to support decommissioning but, where disposal routes are available, this should occur without delay and any interim waste storage should be minimised.
- Radiological clearance is a widespread international practice allowing unrestricted use of materials/waste, including metal recycling and conventional waste disposal.
- Waste repositories are planned or available for most national programmes.
- Regulation of characterisation is primarily undertaken through regulated principles combined with guidance documents.
- Characterisation experience is considered to be fairly extensive but there is considerable scope to embed greater consideration of a life cycle approach to radiological characterisation.

Initiation phase

- Characterisation objectives should be developed from the start of the process (i.e. at the initiation phase) and set out preferably in a detailed characterisation plan, or otherwise in a high-level characterisation strategy.
- During decommissioning planning the most important characterisation objectives are those that contribute towards the development of the decommissioning and waste management (prevention/minimisation, storage, treatment, transport and disposal) plans, as well as cost estimation and safety analyses.
- Once dismantling is taking place the primary objectives of radiological characterisation become waste and hazard management, with waste management generally being most important with the exception of large, and significantly contaminated, facilities/sites.
- Early engagement with the regulatory authorities is critical because characterisation can be crucial to regulatory approval, especially where approval is granted progressively.
- Waste-led decommissioning and associated characterisation, taking into account the characteristics or specifications of the existing available waste routes, potentially saves costs and time.

Planning phase

- A detailed and systematic characterisation plan should be developed, including details of what samples and measurements are required and what analysis (including determinants, acceptable uncertainty and detection limits) should be undertaken.
- When planning characterisation, the planning team and the dismantling experts are judged to be the most important supported by the waste management organisation.
- Operational history and facility documentation are seen as most useful to support characterisation assessments, with characterisation results from previous activities, interviews with operating personnel and radiological inventory data also being important. These are all needed at the planning stage.
- The source of the radioactivity (activation and/or contamination) has the potential to profoundly influence the characterisation plan. Inferred characterisation (using modelled reactor neutron fluxes to estimate radionuclide activity concentrations and knowledge of the composition of facility construction materials) is a key tool for the characterisation of activated facilities, materials and waste, however, the accuracy of models must also be validated using results of sample analysis.
- Vectors/fingerprints of a material or waste are commonly used to estimate hard-to-measure contaminants using measurements of easy-to-measure contaminants multiplied by the relevant scaling factors. However, vectors/fingerprints must be developed on a case-by-case basis (considering the waste type and its operational history e.g. contamination/activation status) and great care is needed in their use as there can be significant temporal (e.g. because of decay and/or radionuclide migration) or spatial variations (e.g. with depth within concrete) in the contaminant concentrations across facilities and within waste streams. Particular consideration should be given to early characterisation where easy-to-measure radionuclides are short-lived (e.g. Co-60) and there is a strategy of deferred dismantling. In these circumstances choice of a longer lived reference radionuclides (e.g. Cs-137) or switching to immediate dismantling may be appropriate.
- Cobalt-60 and Ceasium-137 are the preferred radionuclides for use in correlation of radionuclide vectors/fingerprints, however Americium-241, Uranium-235 and isotopes of plutonium are used to a lesser extent.
- Non-radiological characterisation should be fully considered and can be as important, or more important, than radiological characterisation. Consideration of physical and chemical vectors should form an integral part of a characterisation programme. Examples of such physical and chemical vectors included moisture content, rheology, asbestos, polychlorinated biphenyls (PCBs) and heavy metals.

- Reducing uncertainty about waste and identification of waste classification are generally the highest priorities for characterisation, both of which support securing waste route availability.
- The characterisation programme should be developed and maintained through consideration of the decommissioning strategy and waste management strategy (including treatment, storage, clearance and disposal) both prior to and during dismantling.
- An internal dedicated review process is essential to ensure that characterisation gives statistically robust and representative results. Review by external experts is also important, while benchmarking and networking are useful.

Implementation phase

- The most significant characterisation efforts are put into the characterisation of areas known to be contaminated both prior to and during dismantling.
- The choice of the sampling/measurement locations, to characterise at both the surface and at depth, should be tailored on a case-by-case basis, using specific information about the materials or waste.
- Characterisation, prior to and during dismantling, mainly relies on: dose rate or gamma measurements; sampling followed by gamma, alpha and beta analysis; and the use of in situ handheld beta measurements and volume gamma counter.
- There should be a systematic verification process which checks results on a random basis and when extreme results are identified.
- Review and flexibility of characterisation plans during implementation, taking account of new information and early results, can ensure the characterisation programme remains optimal, still meeting the characterisation objectives, but with potential cost and time savings.

Evaluation phase

- Views are evenly split between the required use of a systematic plan for data assessment and use of a case-by-case approach, presumably reflecting the diverse nature of characterisation challenges which are encountered.
- Material and waste characterisation data should be evaluated using a combination of judgemental and probabilistic approaches, with selection of the appropriate methodology on a case-by-case basis.
- Use of graphical modelling for evaluation and presentation of results is largely adopted by owners and regulators.

- When considering the impact of uncertainties on the evaluation of material and waste, characterisation sampling/measurement representativeness is the most important factor followed by variations in activity distribution and nuclide composition (heterogeneity).
- Laboratory, measurement and quality assurance/independent experts are seen as most important to the data verification and validation process.
- When implementing the data quality assessment process, waste management and quality assurance/independent experts are seen as the most important resources. Radiological expert advice can be important to ensure that results are as expected or, if not, to help to understand why.

Quality assurance

- Characterisation campaigns should have dedicated Quality Assurance Plan developed early on in the characterisation process (during the initiation or planning phases).
- The most important quality assurance measure is developing and following specific documented characterisation arrangements. Other important measures are: review and independent evaluation of characterisation plans; use of accredited laboratories and review of representative sampling. The regulators consider independent control measures and reviews by external experts to be particularly important during the characterisation implementation phase.
- There is wide variation in retention times for samples and characterisation records across all categories of radioactive waste. International guidance may be beneficial in this area.
- Characterisation records are best held on a centralised electronic system but where there is any doubt about the ability to preserve such records, duplicate records in a different form (e.g. paper) should be retained.
- Independent review of characterisation results and evaluation should be undertaken by independent experts.
- Duplication of in situ measurements and analysis by a second laboratory should be conducted for approximately 5% of measurements/analysis.
- Characterisation records management is essential (in particular appropriate retention and the future proofing of access to records), since years and decades may pass between characterisation campaigns and the generation of waste and final disposal.

References

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PREDEC (2016), "International Symposium on Preparation for Decommissioning (PREDEC 2016)", Lyon, France, 16-18 February 2016.

WM Symposia (2016), "Waste Management Symposium", Phoenix, United States, 6-9 March 2016.

Annex B: International conference

Based on an initiative by two task groups within NEA Working Party on Decommissioning and Dismantling, a group of organisations arranged a symposium on "Preparation for Decommissioning". The symposium took place in Lyon, France on 16-18 February 2016 and was named PREDEC (2016).

The symposium was intended to be a forum to:

- learn about current practices;
- highlight strategic issues related to radiological characterisation and decommissioning;
- exchange experiences;
- discuss innovative and new techniques and needs for improvements;
- develop and maintain networks.

In most of the high quality presentations in the seven sessions the importance of radiological characterisation was highlighted. This annex contains a short summary of information given related to this report. It does not provide full coverage.

Introduction

Decommissioning of nuclear facilities is an extensive and multidisciplinary task from initial planning, licensing, detailed planning, through defueling of the reactors and management of the fuel, dismantling of systems and facilities, demolition of structures to the remediation, restoration and release of the site. It was a common view among the speakers and participants that characterisation is crucial in all steps.

Initiation and planning

Decommissioning starts with strategic planning. It is an iterative process and the plans and schedules need to be reviewed and updated as knowledge and experience is gained. Learning from experience has shown the importance of defining the strategy and the initial state as well as the required precision of information early on. It was clearly stated based on experience that early characterisation activities lower the costs and financial risks in a decommissioning programme.

It was said that samples and measurements in early characterisation activities mainly are to confirm and validate what can be assessed from operational records and historical analyses. An early evaluation of historical data can be a valuable starting point to identify where to focus in the characterisation activities.

Speakers highlighted an interdependency between waste management, dismantling and characterisation. Based on the strategic decisions on waste management and dismantling of the facility different information will be needed from the characterisation activities. For this reason it is important to take strategic decisions early on and to define data quality objectives for the characterisation activities.

Decommissioning is to a large extent related to logistics as well as waste and material management. Therefore characterisation and categorisation activities of waste and material are crucial for success. It was reported that successfully managed and well performed characterisation and categorisation campaign may have up to a factor of ten impact on the waste volume for disposal. This will have a massive impact on the total decommissioning and waste disposal costs.

The overall characterisation activities have a large impact on the schedule which is why it is important to start early – the earlier the better. Once the characterisation is completed, other decommissioning activities such as decontamination, dismantling and waste management can be defined, tailored and implemented.

Early characterisation in areas normally classified as inaccessible can in many cases be successfully performed using modelling and calculations. The precision in desk based characterisation of areas close to the reactor core are typically good enough prior to dismantling.

Non-radioactive characterisation was discussed and considered to be of increasing importance. Legislation is increasingly requiring non-radioactive hazardous materials to be accounted for when considering disposal because of the potential environmental impact on groundwater.

Speakers confirmed that characterisation plays a key role in the development of the decommissioning plans, waste management strategies and associated planning costs as well as in reducing the risks of the decommissioning project. Characterisation is also necessary to ensure worker and public safety from radiation and contamination release.

Regulatory representatives from UK reported that the UK has performed a review of radiological characterisation practice across the UK nuclear industry. This included interviewing industry characterisation experts and academics developing new characterisation techniques and used an industry workshop to understand further the challenges and opportunities in characterisation. A range of potential improvements have been identified which will form the basis for future work.

There is an increased reliance and demand on the supply chain within the industry to undertake characterisation work where resources are limited. It has also been found that quality audits appear to focus on the paperwork side of characterisation rather than the practical implementation.

Lessons learnt

A presentation about lessons learnt in a regulatory perspective highlighted the importance of pre-planning for decommissioning by the regulator and continuous dialogue between regulators and those undertaking the characterisation activities.

It is necessary to have a concept of radiological characterisation that includes facility history and the waste management aims.

The overall characterisation of the plant should be completed at an early stage but results should be verified repeatedly throughout the decommissioning project considering the needs and objectives for the actual phases. Experience shows that characterisation competence is needed to the end of the project.

One decommissioning project reported that because characterisation was undertaken during dismantling, instead of before, a ten-year delay to the project occurred as a result of unexpected findings of radioactivity. This affected the entire programme scope, schedule and cost.

The conference was closed with the conclusion that characterisation is one of the most important topics in decommissioning and that further improvements are required to meet the future the needs of an expanding worldwide decommissioning programme.

The conference proceedings, all full papers and presentations are available on the NEA website (www.oecd-nea.org/rwm/wpdd/predec2016).

Annex C: International case studies

Learning from case studies

International case studies (CS) covering a wide range of facilities at differing stages of decommissioning were supplied to the task group to support this work, these are listed in Table C.1. Each of the case studies was reviewed by the task group to identify relevant practices, experiences and learning for each stage of characterisation. The main outcomes from this review are identified in the main chapter text and summarised below under the characterisation phases.

Table C.1: Details of case studies reviewed

Case study	Country of origin	Type of facility, location
CS-01	Belgium	Research reactor, Thetis
CS-02	Spain	Nuclear power plant, Jose Cabrera
CS-03	Korea	Nuclear research reactor, KRR
CS-04	United States	Fuel cycle, Oak Ridge
CS-05	United States	Fuel cycle, Hanford Site
CS-06	Japan	Nuclear power plant, Hamaoka
CS-07	Sweden	Fuel cycle, Ranstad
CS-08	United Kingdom	Nuclear power plant, Calder Hall
CS-09	Germany	Nuclear power plant, Stade
CS-10	Norway	Reactor decommissioning concept
CS-11	United Kingdom	Fuel cycle, Sellafield
CS-12	Italy	Nuclear power plant, Caorso
CS-13	United States	Waste treatment, WVDP

Initiation phase

- The final destination of the material/waste was taken into account in order to optimise the efficiency and effectiveness of the project (e.g. characterisation results produced during dismantling were used in later stages of the decommissioning/building release process) (CS-01).
- Characterisation objectives were established and included, among others: identification of the impacted areas, nature and extension of the contamination, evaluation of the waste management alternatives and impacts (public and occupational) of the dismantling, selection and evaluation of the decontamination processes and planning the works of point of view ALARA (CS-02).
- It is relevant to have information about changes in facilities given they can complicate characterisation efforts, especially if they are not well documented. Additionally, the presence of radioactive waste during the transition phase should be conveniently considered because the inventory may be overestimated (CS-02).
- Learning from the project shows good agreement between expected and real inventories, mainly for activation products, is a key element for the efficient decommissioning development avoiding unnecessary deviations of costs and schedules (CS-02).
- Information from previous characterisation campaigns was used as input data for decommissioning design, plan and implementation of the decommissioning project (CS-03).
- A detailed investigation of the facilities to be decommissioned was carried out as the first-step of a project to plan the decommissioning of the research reactors and their auxiliary facilities. By reviewing the characteristic data it was possible to extract the input data for a decommissioning plan leading to implementation of the decommissioning project (CS-03).
- Characterisation data were used to bound the expected conditions during demolition activities, to model aerial discharges, to develop waste profiles supporting treatment and disposal and to establish personnel protection requirements (CS-05).
- Characterisation data were used to define the dismantling method, to evaluate waste management options, dose impact for workers and public, to collect data for the safety review of the disposal facility and to support development of a database for the national inspection and for design/ safety reviews for conditioning facilities (CS-06).
- Combination of measurement and calculations will produce accurate information of radiological inventory of material. By undertaking a combination of physical and calculation techniques it is possible to refine the estimates (CS-03) and (CS-06).

- Characterisation can be used to meet specific project objectives, for example by providing data of sufficiently quality to inform decommissioning decisions (CS-07).
- Engagement with decision makers and stakeholders is important and should start at the initiation phase. (CS-08).
- It is important to have clearly defined objectives for the project as these will inform the characterisation process including sampling and analysis schedules, cost estimation and stakeholder acceptance (CS-08).
- Constraints identified – some technical systems could only be sampled during dismantling. Methods/approach detailed in site licence. Different licence conditions for technical systems and building fabric. Objective was clearance/waste management (CS-09).
- Characterisation can be used to increase understanding of the levels of contamination in a material in order to challenge assumed disposal options and thus apply the waste management hierarchy. Setting clear objectives will help focus the characterisation work and inform final waste disposal options as well as future characterisation needs of similar facilities/material (CS-11).
- Understanding the full characterisation needs early, for example non-radiological hazards, allows these to be incorporated into the plan therefore limiting rework in terms of sample collection, worker access and additional costs (CS-13).
- The characterisation methodology and techniques used are informed by the waste classification and ultimate disposal destination (CS-13).
- Established personnel radiological exposure goals which would allow meet requirements of NESHAPS-CAP88 and therefore allow demolition of the buildings (CS-13).

Planning phase

- Operational data (standard operational records, potential incident reporting, licence documentation, feedback from operational workers, etc.), additional radiological surveys, neutron activation and other calculations for scaling factor determination were used to draw up a detailed inventory. Preliminary classification per type of material and estimated final destination were used to develop the decommissioning (and characterisation) plans (CS-01).
- Characterisation work has been progressed in parallel with a decommissioning plan in order to guide both the planning and implementation phases. The process followed was to identify and measure areas of contamination in order to evaluate waste management options and assess the impact to both workers and public. Waste management was based on the results of the characterisation and its comparison with acceptance criteria (CS-02).

- Review of historical operational information, including unexpected events and results from previous characterisation surveys, was undertaken in order to develop preliminary list of radionuclides of concern for inclusion in scope of characterisation work and contamination classification of areas of the facility. Review supplemented with interviews with workers and theoretical activation calculations. Development of characterisation plan which outlines the main objectives, strategies and methods to carry out the characterisation activities along the decommissioning project. The level of survey effort is based on the potential for contamination that converts the zonal classification in a critical step of the survey design (CS-02) and (CS-09).
- Historical data assessment consisted of review of licensed radioactive materials, review of operational records and operator interviews. It is concluded that there is insufficient information of operation history records and documents for characterising the facility for planning the decommissioning of KRR-1&2, which will inform the characterisation needs of the future project (CS-03).
- Operation/maintenance and historical data detailing normal operation abnormal operations is useful to inform characterisation needs and measurement/sampling activities. However, it results from characterisation may find areas/levels of contamination that were not expected, which will need to be reviewed and understood. Equipment maintenance records are also a useful source of information to inform dismantling/decommissioning of equipment which would be difficult to characterise in situ (CS-03).
- Operational history was used to identify both contaminants of concern and releases which may have occurred – this led to a "biased" characterisation plan – targeted towards areas of concern (CS-04) and (CS-13).
- Characterisation encompassed numerous cycles of sample collection, sample analysis and data evaluation for radiological and non-radiological constituents. Development of a sampling and analysis plan was informed through evaluation of the facility history (construction materials), contamination from biological intrusion, radiological and industrial surveys, review of historical information including unexpected events (CS-05).
- Core sampling and radiochemical analysis was planned to verify theoretical calculations. Number of campaigns/status of plant: 3/operation and 2/during decommissioning (CS-06).
- The accuracy of calculations can be improved by review of neutron irradiation history, historical operational information, facility history, neutron transport calculations, dose rate etc. (CS-06).
- Retired staff, with knowledge of historical operations, are an important source of information to better understand condition and contamination of a facility as are archived documentation (including technical drawings) (CS-07).

- Review of historical data is important to identify gaps which may need to be addressed by future characterisation activities (CS-08).
- Characterisation of equipment and building structures may be undertaken following different methodology, for example focus on contamination and/or activation depending on materials and operational history (CS-09).
- Learning from projects can be shared to inform future decommissioning of other facilities (CS-10).
- Characterisation was planned using historical information, activation code modelling and preliminary characterisation to group materials for which a similar scaling factor methodology can be used (CS-12).
- Good characterisation planning based on accurate evaluation of historical data can reduce time and cost and directly affect the whole approach to decommissioning (CS-12).
- Although historical information is useful it is crucial that this is reviewed to ensure it meets current regulatory requirements (CS-13).

Implementation phase

- Characterisation of selective fuel assemblies (including fuel, fuel cladding and graphite plugs) was performed using depletion and activation calculations to determine specific radionuclide concentrations. Results were verified by comparing calculated to measured dose rates showing good correlation for centre of fuel elements and some over estimation of radioactivity for graphite plugs and ends of fuel elements (CS-01).
- Characterisation of selective reactor components was performed using activation calculations to determine the radionuclide composition and determine scaling factors relative to Co-60. Co-60 measurements using high purity germanium (HPGe) detectors were then performed and the derived scaling factors were used to estimate radionuclide concentrations of reactor components to inform waste routing and disposal options (CS-01).
- Characterisation mapping of the entire stainless steel liner was undertaken in situ using gamma spectrometry with activated waste routed for conditional (melting) release. The outer face of the concrete structure was mapped using in situ gamma spectroscopy combined with calibration software and characterised using depth drilled samples. Unexpectedly, the concrete base was found to contain activation products changing the decommissioning and waste strategy from immediate unconditional release to decay storage. Subsequent investigation determined that there had been an error in the model for neutron activation calculation (CS-01).
- Sampling and measurements plans were based on graded approach and risk. Characterisation techniques employed were analysis of wipe tests by gamma spectrometry and liquid scintillation analysis. The sampling density was based on four contamination risk categories (CS-01).

- Several characterisation campaigns addressed to a specific media (structures/systems/components, outdoor areas and decontamination actions) (2/operation, 3/transition and 3/during decommissioning). As the project progresses, the objectives related to material and lands management gain in importance (CS-02).
- Radiation dose rate and surface contamination of equipment, floors and walls of the facility as well as the surface of activated materials within the reactor pool structure were measured and evaluated by sampling, wipe testing, in situ gamma spectrometry, etc. (CS-03).
- Activation calculations were performed by the British Nuclear Fuels Limited (BNFL) making use of the ORIGEN computer code to estimate the residual radioactivity of reactor pool structures and components. The evaluation of the results of the activation inventory for reactor internals and shielding concrete showed quite discrepancy between the calculations and the sampling results during decommissioning thus informing the needs of future characterisation (CS-03).
- Production of a site conceptual model is a useful method to describe contamination across a facility (CS-04).
- Operations began with initial characterisation activities, utility isolations, followed by the start of hazardous material removal. Hazardous material removal encompassed a broad spectrum of substances ranging from asbestos, heavy metals, oils, lights/lamps, to radioactive materials (CS-05).
- Extensive pre-demolition and in-process characterisation has established a baseline of data used in establishing contaminants of concern (COCs). COCs are radiologicals that are associated with reactor operations and nuclear fuel and include chemical constituents (Am-241, Pu-238, Pu-239, Pu-240, Pu-241, Cs-137, Sr-90, Co-60, H-3, I-129,Tc-99, Cd, Cr, Cr(VI), Pb, Sb, Se, U (total), Cn, Nitrate, etc.). Extensive inspection, sampling and radiological survey were conducted throughout the course of building characterisation and demolition (CS-05).
- Lower primary containment characterisation will consist of boring ten concrete cores at selected locations and obtaining two samples from each core. Each core will be bored between one to two feet below the original floor face, but at a minimum of one foot. The two sample locations on each core include the original floor face and the bottom of the core, which will be sampled in order to examine whether or not tritium contamination diffused into the structural concrete (CS-05).
- Characterisation methodologies can include: monitoring of radiation doses, dose equivalent, concentrations of radioactive materials, density etc. (CS-06).
- Uranium Works: Surface contamination measured using scintillation detectors calibrated using gamma spectrometry. Wipe tests used to collect and measure loose surface contamination. Gamma spectrometry and inductively coupled plasma mass spectrometry (ICPMS) used to determine scaling factors and bulk waste activity concentrations (CS-07).

- Uranium and daughter measurements are difficult, particularly in an environment with abundant uranium background levels and therefore require careful characterisation planning and input from experienced staff (CS-07).
- Development of sampling methodology and techniques will be based on nuclide composition and need (CS-08).
- A representative sample set is fundamental to ensure characterisation campaigns are suitable to achieve project objectives. Statistical tests are useful to determine contamination distribution (CS-09).
- Materials segregated with respect to type, nuclide vector and clearance option and informed by characterisation (CS-09).
- The characterisation exercise followed a systematic eight-stage plan that led to the analysis of over 650 samples collected over a seven-year period, as well as historical data (CS-11).
- Removal of contaminated structures reduced background radioactivity therefore allowing characterisation lower activity components (CS-13).

Data assessment phase

- The release process for the building was based on a graded approach following the philosophy of DIN 25457-6 (CS-01).
- The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) approach was used for clearance and to inform final site survey processes, sampling and measurement requirements as well as quality assurance and data assessment approach (CS-02).
- The final status survey for site release will be carried out based on the MARSSIM and Environmental Radiation Survey and Site Execution Manual (EURSSEM) method with various measuring methods of sampling and in situ measurement (CS-03).
- Data assessment found discrepancy between results from sampling and calculation campaigns, which will inform future characterisation projects (CS-03).
- Paint and steel samples were analysed separately but combined for bulk clearance purposes (CS-08).
- DIN ISO 11 929 was used to prepare sampling and analysis plans (CS-09).
- The suitability of scaling factors were confirmed by Co-60:Am-241 correlation (CS-09).
- GIS is a powerful tool for the visualisation and trending of large data sets (CS-11).

Quality assurance

- A material database system was implemented to track all materials from initial collection to final destination (CS-01).
- An integrated database was developed to store all plans, historical information and results, thus allowing all information to be made available throughout the project in a consistent format (CS-02).
- Change control was employed to capture any changes to sampling plan and inform key stakeholders (CS-04).
- Independent review and checking was employed at all stages of project (CS-09).

Standards and guidance – references

- ISO 11929:2010 Determination of the characteristic limits (decision threshold, detection limit and limits of the confidence interval) for measurements of ionising radiation – Fundamentals and application (CS-01).
- Standard: DIN 25457-6: Activity measurement methods in the clearance of radioactive waste substances and nuclear facility components – Part 6: Rubble and buildings (CS-09).
- MARSSIM approach for clearance and final site survey processes, sampling and measurement requirements and quality assurance and data assessment approach (CS-012).
- EURSSEM (together with MARSSIM) for final status survey for site release (CS-02 and CS-03).
- UK Environmental Permitting Regulations (CS-08).
- Local procedures for characterisation (SLSP 1.07.35) and waste clearance (SLP 2.10.114) (CS-08).
- Guidance from NICoP and RP89 (CS-08).
- DIN ISO 11 929 (CS-09).
- ISO17025 (CS-12).
- Ministry of Finance (FIN) guidelines for planning major public investment projects (CS-10).
- Local procedures for characterisation (SLSP 1.07.35) and guidance from NICoP (CS-11).
- MARSSIM NUREG-1575 (CS-13).
- NESHAPS-CAP88 (CS-13).

Annex D: International standards and guidance

Introduction

A wide range of international and national standards and guidance have been published to inform radiological characterisation which have relevance from a materials and waste end states perspective. To inform the exploration of the strategic and more practical aspects of radiological characterisation, international and national regulations, standards and guiding documents have been collated and analysed. An overview of national approaches to characterisation standards and guidance for 11 NEA member countries is given below together with references to the main documents which are used.

Belgium

There is no specific regulatory guidance on radiological characterisation for decommissioning in Belgium, but it is embedded in more general guidance documents on decommissioning and clearance. At the regulatory level, the Federal Agency for Nuclear Control (FANC) Royal Decree of 30/11/2011 (FANC, 2011) specifies that an inventory is required containing all radioactive material used during operation and all radioactive waste produced and still to be evacuated. The physical and chemical nature, as well as the radiological characteristics should be mentioned and the foreseen destination. This is in line with the requirements from the Belgian Waste Management Agency (NIRAS/ONDRAF, 1981).

In practice, operators use classification and sampling methods (e.g. for buildings) based on MARSSIM (NRC, 2000) or a Deutsches Institut für Normung (DIN) e. V. standard (DIN, 2015). Generic mass specific clearance levels are specified in the FANC Royal Decree of 20/07/2001 (FANC, 2001), based on RP-122 (EC, 2000a). No surface specific clearance levels are defined at the regulatory level. A FANC decree (FANC, 2010) acts as a guidance for measurement procedures and techniques to verify compliance with clearance levels as defined in RD2001 (FANC, 2001). In practice, RP-113 (EC, 2000b) is accepted for clearance of buildings. Radiological characterisation of waste is regulated by the Belgian Waste Management Agency) in their royal decrees (NIRAS/ONDRAF, 1981, 2002).

References

DIN (2015), "Activity Measurement Methods in the Clearance of Radioactive Waste Substances and Nuclear Facility Components – Part 6: Rubble and buildings", DIN-25457-6.

EC (2000a), "Practical use of the Concepts of Clearance and Exemption: Part I: Guidance on General Clearance Levels for Practices", Radiation Protection 122.

EC (2000b), "Recommended Radiological Protection Criteria for the Clearance of Buildings and Building Rubble from the Dismantling of Nuclear Installations", Radiation Protection 113.

FANC (2011), "Royal Decree of 30 November 2011 on the safety requirements for nuclear installations".

FANC (2010), "FANC Decree of 30/04/2010".

FANC (2001), "Royal Decree of 20 July 2001 laying down the General Regulation for the protection of the public, workers and the environment against the hazards of ionizing radiation, as amended".

NIRAS/ONDRAF (2002), "NIRAS/ONDRAF Royal Decree of 18/11/2002".

NIRAS/ONDRAF (1981), "NIRAS/ONDRAF Royal Decree of 30/03/1981".

NRC (2000), "Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)", Rev. 1, August 2000.

Canada

In Canada, high-level requirements for conducting surveys and characterising the facilities are set in the Regulatory Guide G-219 (CNSC, 2000) and CSA N294-09 (reaffirmed 2014) (CSA, 2014a). The results of the surveys provide the basis for decommissioning planning, however the practices and methodologies to be used are not specified in the documentation. The clearance levels for nuclear substances and materials are set in the Canadian Nuclear Safety Commission's (CNSC) *Nuclear Substances and Radiation Devices Regulations*. They align with international standards for exemption and clearance of nuclear substances from licensed activities. CSA 292.0-14 (CSA, 2014b) is part of a series of standards on radioactive waste management and provides guidance on waste characterisation methods. CSA N292.5-11 (CSA, 2011) provides direction for the application of the exemption quantity and clearance level criteria for the release of materials containing, or potentially containing nuclear substances and the activities necessary to demonstrate compliance with these criteria. The CNSC is undertaking a modernisation of its regulatory framework and as part of this is planning to update its waste and decommissioning regulatory documents and to harmonise its requirements for surface contamination criteria.

References

CNSC (2000), *Decommissioning Planning for Licensed Activities*, Regulatory Guide G-219, CNSC, Ottawa.

CSA (2014a), *Decommissioning of Facilities Containing Nuclear Substances,* N294-09, CSA, Mississauga.

CSA (2014b), *General Principals for the Management of Radioactive Waste and Irradiated Fuel,* N294-0-14, CSA, Mississauga.

CSA (2011), *Guideline for the Exemption or Clearance from Regulatory Control of Materials that Contain, or Potentially Contain Nuclear Substances,* N292.5-11, CSA, Mississauga.

France

The nuclear industry is driven by regulatory guides from the French Nuclear Safety Authority (ASN). Guide 6 (ASN, 2016a) deals with the overall decommissioning and dismantling framework. Guide 14 (ASN, 2016b) and more recently Guide 24 (ASN, 2016d) present the mandatory actions for the radiological characterisation of buildings and soils, respectively. Guide 23 (ASN, 2016c) on the establishment and changes in waste zoning plans provides the prerequisite for clean-up operations for basic nuclear installation.

These guides are regularly updated taking into account industry feedback and developments in the regulatory approach. However, these guides are more focused on the final end-state rather than taking a life cycle approach to characterisation. On the contrary, individual decommissioning decrees insist on taking a global approach to waste management.

IRSN provides a more detailed and technical guide for the characterisation of contaminated sites (IRSN, 2011).

In addition, the French National Radioactive Management Agency (ANDRA) has defined detailed specifications for the waste packages for the different disposal facilities. Disposal facilities are available for low-level short-lived, intermediate-level short-lived and very-low-level waste and are under development for low-level long-lived, intermediate-level long-lived and high-level waste. These specifications force the producers to characterise their waste.

However, France has not adopted clearance levels and consequently, a case-by-case approach is adopted to the boundary of nuclear facility where materials and waste must be treated as being radioactive. This can lead to difficulties in ensuring that a consistent approach is taken. Furthermore, there is no unified methodology between the different nuclear operators despite several working groups and technical meetings. This generally leads to a case-by-case approach, with significant discrepancies for targeted radiological thresholds for instance.

References

ASN (2016a), “Arrêt définitif, démantèlement et déclassement des installations nucléaires de base en France” (Shutdown, dismantling and decommissioning of nuclear facilities), Guide 6.

ASN (2016b), “Assainissement des structures dans les INB” (Cleaning of structure in a basic nuclear installation), Guide 14.

ASN (2016c), “Etablissement et modification du plan de zonage déchets des installations nucléaires de base” (Definition and modification of the waste zoning plan of basic nuclear installation), Guide 23.

ASN (2016d), “Gestion des sols pollués par les activités d’une INB” (Management of polluted soil from basic nuclear installation activities”), Guide 24.

IRSN (2011), “Gestion des sites potentiellement pollués par des substances radioactives” (Methodology guide for the management of sites potentially contaminated by radioactive substances).

Germany

In Germany there are no special guidelines in the nuclear field regarding how to undertake radiological characterisation. In accordance with the Atomic Law it is necessary to fulfil the requirements for the granting of a decommissioning licence. A key aspect of this is the verification that hazards have been prevented. Therefore it is essential to determine the whole amount of activity which has to be handled. Hence it is common during the decommissioning licensing procedure to describe the total activity inventory, a sampling plan and the methods to establish nuclide vectors. This will be reviewed and come into force with the licence.

Since the dismantling of the facility needs a licence, it is not common to dismantle parts ahead of the granting of the licence. But concerning radiological characterisation, there is advice relating to the taking of samples before licensing at least to verify the activation calculation (BfE, 2016). Other guidance (ESK, 2015) sets out the aims of the characterisation and the timeline for the different steps. The timeline is similar to that which is described in the Task Group on Radiological Characterisation and Decommissioning (TG-RCD) Phase 1 report. Some standards (DIN, DIN ISO, EN) give practical instructions for sampling, measurement and quality assurance. Especially for clearance there is an article (§ 29) in the Radiation Protection Ordinance (BfS, 2016), which gives instructions how clearance could be performed and also gives the table of clearance values. The performance of clearance is ruled by a note from the regulatory body. In this note the regulatory expectations for radiological characterisation are set out and used for regulation.

The main reference guidelines and other guidelines for decommissioning in Germany from the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety Statements and Recommendations of the Nuclear Waste Management Commission are listed below.

References

BfE (2016), “Guide to the decommissioning, the safe enclosure and the dismantling of facilities or parts thereof as defined in § 7 of the Atomic Energy Act” (*Leitfaden zur Stilllegung, zum sicheren Einschluss und zum Abbau von Anlagen oder Anlagenteilen nach § 7 des Atomgesetzes vom 23.06.2016*), BAnz. AT 19.07.2016 B7.

BfS (2016), “Ordinance on the Protection against Damage and Injuries Caused by Ionizing Radiation (Radiation Protection Ordinance)”, BGBl. I 2016, No. 37.

ESK (2015), “Guidelines for the decommissioning of nuclear facilities – Recommendation of the Nuclear Waste Management Commission (ESK) of 16.03.2015” (*Leitlinien zur Stilllegung kerntechnischer Anlagen – Empfehlung der Entsorgungskommission vom 16.03.2015*).

ESK (2013a), "ESK Guidelines for the storage of radioactive waste with negligible heat generation (revised version of 10.06.2013) – Recommendation of the Nuclear Waste Management Commission (ESK)" (*ESK-Leitlinien für die Zwischenlagerung von radioaktiven Abfällen mit vernachlässigbarer Wärmeentwicklung; Revidierte Fassung vom 10.06.2013 – Empfehlung der Entsorgungskommission*).

ESK (2013b), "ESK stress test for nuclear fuel cycle facilities in Germany, Part 2: Storage facilities for low- and intermediate-level radioactive waste, stationarz facilities for the conditioning of low- and intermediate level radioactive waste, disposal facilities for radioactive waste, revised version of 18.10.2013 – Statement of the Nuclear WAste Management Commission" (*ESK-Stresstest für Anlagen und Einrichtungen der Ver- und Entsorgung in Deutschland Teil 2, "Lager für schwach und mittelradioaktive Abfälle, stationäre Einrichtungen zur Konditionierung schwach und mittelradioaktiver Abfälle, Endlager für radioaktive Abfälle"; Stellungnahme der Entsorgungskommission; revidierte Fassung vom 18.10.2013*).

Italy

In Italy there is no specific guidance to support the radiological characterisation within the nuclear industry but, attached to the authorisation decrees, for the decommissioning of a nuclear power plant or, generally, a nuclear facility, are included prescriptions, requested by the Nuclear Competent Regulatory Authority, for the various radiological characterisation's steps.

Specifically, the radiological characterisation of a facility allows the creation of a repository of information on the amount and type of radionuclides present in the facility itself as a result of its exercise, on their distribution and their physical and chemical states.

In a nuclear facility under decommissioning, radiological characterisation allows the planning and design of the decommissioning operational phases such as decontamination, dismantling and removal of components and structures, the management of waste arising from the dismantling as well as to estimate the radiological inventories and its associated costs.

The radiological characterisation of a facility represents a sequential process which includes the following steps:

- the recovery of all the historical information;
- the development and application of methods of calculation;
- the preparation of a sampling plan;
- execution field measurements, sampling and analysis of samples;
- the evaluation of the data obtained;
- comparison of the measured data and those resulting from calculations.

Regarding the aforementioned steps, a specific radiological characterisation plan is prepared. The plan is continually updated based on the latest available data and technological advancement.

The specific radiological characterisation plans, either for waste and materials' clearance, have to be approved by the Nuclear Competent Regulatory Authority.

Generally the MARSSIM approach and specific national and international standards are followed for radiological characterisation (UNI, ISO, European Recommendations) which give practical instructions for sampling, measurement and quality assurance. In particular, all steps and procedures carried out to establish the radioactivity of samples are traceable as specified in ISO/IEC 17025. This implies, for example, a complete documentation of the sampling strategy, the sampling plan chosen and the analytical protocol and all steps undertaken during analysis. The measurement procedures ensure the use of certified reference materials, the participation in inter-laboratory comparisons and proficiency testing. For any measurement result, the standard uncertainty associated with it is determinate in accordance with ISO/IEC Guide 98-3:2008 "Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement", taking into account all known sources of uncertainty.

For materials' clearance, a specific technical guide developed by the Nuclear Competent Regulatory Authority is under development.

Japan

Japan regulatory guidance for nuclear facilities is available to judge the measurement method of radioactive concentration and evaluation method which are appropriate for clearance (NRA, 2011).

Standards of the Atomic Energy Society of Japan (AESJ) for nuclear facilities are available to support formulation for technical rules of measurement and judgement methods for clearance (AESJ, 2005, 2010).

References

AESJ (2010), *Method of the Clearance Level Verification in Uranium Processing Facilities: 2010* (in Japanese), AESJ-SC-F020.

AESJ (2005), *Monitoring for Compliance with Clearance Level: 2005* (in Japanese), AESJ-SC-F005, AESJ, Minato-ku.

NRA (2011), *Houshanounoudo no sokutei oyobi hyouka no houhou no ninka ni tsuite* (Regarding approval for measurement and evaluation method of radioactive concentration), Regulatory Guide, (in Japanese).

Spain

In Spain the application for the operating and dismantling permits shall be accompanied for documents related to the radioactive waste management: the radioactive waste and spent fuel management plan and, specifically for the decommissioning, the clearable materials control plan. These documents include the methodology to perform the radiological characterisation of the residual materials and a consensus in the use of international guidance is established.

Additionally, the safety case for dismantling permit includes an updated description of the installation, the site and surrounding area with the radiological characterisation of the installation and the site prior the decommissioning.

From the point of view of the radioactive waste management, the residual materials are categorised as impacted (contaminated or activated) and non-impacted based on the establishment of the radioactive waste areas. This approach recognised at the national legislation is similar to the French practices but it is not exactly the preferred for the clearance methodology where American guides are applied.

The only waste disposal option currently available in Spain is the "El Cabril" near-surface land repository. This repository is designed to accept very low, medium and intermediate-level waste, in accordance with the corresponding "acceptance criteria", issued by Enresa as owner and operator of the facility. According to these acceptance criteria, radioactive waste may be classified as RBBA (very low-level waste), RBMA (low- and intermediate-level waste [LILW]) levels 1 and 2. This classification is based upon the content of both long and short-lived radionuclides.

Waste which do not comply with RBMA level 2 limits (hereafter called Non-LILW) are considered as not acceptable for near-surface disposal. In this regard, they may be considered as equivalent to greater than class C in the United States, and, like the latter, must be disposed of in a future geologic repository.

The unconditional (EC, 2000a) and conditional (EC, 1989, 2000b) clearance levels applied are included in the European Commission recommendations and a number of international (US) guidance documents are used (NRC, 2000, 2009 and 2006; EPA, 2006; ANSI, 2008; ISO, 2007).

References

ANSI (2008), "Characterization in Support of Decommissioning Using the Data Quality Objectives Process", ANSI/HPS 13.59.

EC (2000a), "Practical use of the Concepts of Clearance and Exemption. Part I: Guidance on General Clearance Levels for Practices", Radiation Protection 122.

EC (2000b), "Recommended Radiological Protection Criteria for the Clearance of Building and Building Rubble from the Dismantling of Nuclear Installations" (2000), Radiation Protection 113.

EC (1989), "Recommended Radiological Protection Criteria for the Recycling of Metals from the Dismantling of Nuclear Installations", Radiation Protection 89.

EPA (2006), "Guidance on Systematic Planning Using the Data Quality Objectives Process", EPA QA/G-4.

ISO (2007), *Scaling Factor Method to Determine the Radioactivity of Low- and Intermediate-level Radioactive Waste Packages Generated at Nuclear Power Plants*, ISO:21238, Geneva.

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Sweden

The Swedish nuclear industry has jointly developed two handbooks on the clearance process. One important part of the clearance process, and by then central in the handbooks, is the radiological characterisation and categorisation. The first guiding handbook (SKB, 2011) was developed in parallel with the new regulation on clearance and published in 2011 and cover the topic in general. In 2016, a second handbook (SKB, 2016) was published focusing on clearance in decommissioning. This handbook covers general aspects of characterisation as well guidance how to apply statistical methods in characterisation, clearance and waste management.

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Chinese Taipei

Chinese Taipei has already the capabilities of conducting nuclear reactor facilities radiological characterisation, derived concentration guidance levels (DCGLs) derivations, and measurement techniques associated with radioactive waste free release, which will be applied in the nuclear power plant decommissioning operation in the future.

Referring to IAEA Standards (IAEA, 2004), Chinese Taipei had developed a guide titled: "Administrative Regulations for Radioactive Waste below Certain Activity or Specific Activity" (ROC, 2004), as a basis for implementing the clearance of radioactive waste. In response to the decommissioning of the Taiwan Research Reactor (TRR), Chinese Taipei established the Clearance Measurement Laboratory, measuring instrument calibration and quality control techniques, radioactive waste drum counting techniques and completed related technical reports (Yuan et al., 2009; Yeh et al., 2012), operation procedures (ROC, 2014b), etc. In the period of 2007-2011, the release operation of 2 278 tonnes of concrete and 140 tonnes of scrap metal had been completed and that demonstrated Chinese Taipei's practical experiences and mature technical capabilities in implementing radioactive waste free release.

According to the Nuclear Reactor Facilities Regulation Act (ROC, 2003b), the decommissioning plan shall be submitted by the licensee three years prior to the scheduled permanent shutdown of nuclear reactor facilities, and the decommissioning plan should specify the radiation characterisation survey method and the preliminary evaluation results of the site and the facilities (ROC, 2012, 2014a). After the decommissioning of the nuclear reactors, the sites are classified as "restrictive use" and "non-restrictive use" based on radiation dose limits (ROC, 2003a).

Currently, the preliminary characterisation surveys described in the decommissioning plan are based on the recommendations from MARSSIM (NRC, 2000) and MARSAME (NRC, 2009) of United States. The concept of Survey Package is employed to conduct a systematic planning for radiation survey and contamination investigations. The survey results are to be recorded, reviewed and saved according to the quality control procedure requirements. In addition, through the co-operation with Argonne National Laboratory (ANL), the dosimetry simulation code assessment techniques such as residual radiation (RESRAD) (on-site)/RESRAD-build have been established for the derived concentration guidance levels (DCGLs) which will be used as the basis of legal release after the final status surveys (FSSs) on the site. The related technologies and methods that have been established will also be applied in radiological characterisation surveys to be conducted after the permanent shutdown of the nuclear power plant.

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United Kingdom

UK regulatory and industry guidance is available to support radiological characterisation within the nuclear industry. Typically the standards and guidance either set out top level regulatory expectations (EA, 2010, 2015) or provide detailed guidance on sub-topics of the characterisation process (UK Nuclear Industry, 2012). In practice this has led to a reliance on international guidance or company procedures to support areas where prescription not available. For example, IAEA (2007) and NEA (2013) documents are being used to support strategic planning and the data quality objectives methodology (EPA, 2006) to inform the development of characterisation strategies and plans. Without a national consensus regarding the applicability of wider guidance, this situation can lead to inconsistencies in characterisation practice and/or the implementation of approaches that do not align with the UK's needs. These matters have been recognised through a recent national review and are being addressed through the development of a Nuclear Industry Code of Practice for Characterisation.

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United States

The United States has developed guidance documents like the Multi-Agency Survey and Site Investigation Manual (MARSSIM) and Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual (MARSAME) that are used to carry out the characterisation surveys and support the clearance process. As many of country's ageing nuclear facilities undergo decontamination and decommissioning (D&D), state and federal government agencies in the United States carry out objective characterisation surveys to define the extent of radiological contamination at designated sites. Characterisation surveys use the data quality objectives process and the data collection efforts are streamlined. The process allows more resources to be spent on actual clean-up and risk reduction than data collection efforts. ANSI N13.59 standard (ANSI, 2008), "Characterisation in Support of Decommissioning Using the Data Quality Objectives Process", provides detailed technical approaches for designing characterisation activities. The characterisation surveys approach used in the United States benefit the D&D projects by reducing uncertainty in the estimates of contaminated land and facilities, allowing evaluation of various clean-up alternatives (unrestricted vs. restricted release), ensuring minimal safety and health impact to clean-up workers and the environment, producing reliable estimates of radioactive waste volumes generated during D&D activities, and greatly enhancing credibility in the characterisation results and building stakeholder trust in environmental clean-up activities. Overall a large number of guiding documents have been developed by US organisations which are used within the United States and internationally (CFR, 1993; DOE, 1982, 1987, 1990, 1992, 1994 1995, 1996, 1998, 2000, 2011a and 2011b; EPA, 2006a and 2006b; NRC, 2000, 2006 and 2009).

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Radiological Characterisation from a Waste and Materials End-State Perspective

Radiological characterisation is a key enabling activity for the planning and implementation of nuclear facility decommissioning. Effective characterisation allows the extent, location and nature of contamination to be determined and provides crucial information for facility dismantling, the management of material and waste arisings, the protection of workers, the public and the environment, and associated cost estimations.

This report will be useful for characterisation practitioners who carry out tactical planning, preparation, optimisation and implementation of characterisation to support the decommissioning of nuclear facilities and the management of associated materials and waste. It compiles recent experience from NEA member countries in radiological characterisation, including from international experts, international case studies, an international conference, and international standards and guidance. Using this comprehensive evidence base, the report identifies relevant good practice and provides practical advice covering all stages of the characterisation process.

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