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Clearance during dismantling and demolition of nuclear facilities

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The original report, dated August 2017, was found to contain editorial errors which have been corrected in this updated version.

Preface

This report describes a proposed methodology for clearance (in accordance with SSMFS 2011:2 (SSM 2011)) in conjunction with dismantling and demolition of nuclear facilities. The report is aimed at those who work with planning and management of decommissioning and clearance projects and should be seen as a complement to the existing practice that is described in the Clearance Manual (SKB 2011).

The report is based on four background reports developed in cooperation with expertise (see Table F-1) in different disciplines with experience from major clearance projects in Sweden such as

- clearance of the central active laboratory (ACL) in Studsvik,
- clearance of the leaching and sorting plant in Ranstad,
- clearance of turbine rotors at Ringhals,
- clearance of m/s Sigyn.

Table F-1. List of contributions to the report.

Chapter	Author	Organisation
4–8	Per Lidar, Arne Larsson, Olga Korneevets and Klas Lundgren	Studsvik Nuclear AB
9	Tommy Norberg	Chalmers University of Technology
11	Simon Duniec and Per-Olof Aronsson	Energy Solutions
12	Miranda Keith-Roach, Maria Lindgren and Mark Elert	Kemakta Konsult AB

Since the experience from clearance of nuclear facilities in Sweden is limited, the report also contains information and recommendations from international standards and guidance documents from other countries (MARSSIM (NRC 2000), NiCoP (SDF 2005)). The proposed methodology will most likely need to be revised as nuclear facilities are dismantled and demolished in Sweden. Only when the methodology has been tested practically, a practice can be established for clearance during dismantling and demolition of nuclear facilities.

Contents

1 Introduction

In conjunction with planning of and actual decommissioning, many activities are governed by the facility's radiological status. Therefore, clearance and associated activities (for example radiological survey, decontamination and clearance measurement) have a central role during a decommissioning project.

Today, the Clearance Manual (SKB 2011) is used as a basis for clearance of materials generated during operation of the Swedish nuclear facilities. During dismantling and demolition, clearance of materials may entail logistic challenges, when large quantities of material need to be cleared in a relatively short time. Measurement methods and analyses will, however, not necessarily differ from those used today for clearance of materials from operation. This report focuses therefore on clearance of buildings, rooms and land, where an efficient measurement and analysis procedure will be of great importance for avoiding extended clearance projects, with increased decommissioning costs as a result.

The report generally refers to contaminated objects or objects risking contamination. In conjunction with determination of radioactivity, activation must also be considered. It will, however, only concern a small fraction of the objects that will be subject to clearance during dismantling and demolition, because materials that have been activated often have activity levels that, by a large margin, exceed the limit for clearance (one exception is parts of the biological shield, which may be considered for clearance). Therefore, the report mainly focuses on contaminated objects.

Chapter 2 describes the clearance process and its activities, as well as how clearance should be incorporated into the overall decommissioning process. Chapter 3 describes the risk categories that are used throughout the clearance process in order to effectively adapt the work in each stage. Initial assessment and radiological survey of objects are described in Chapter 4. Preparations for clearance measurement are outlined in Chapter 5 (decontamination) and 6 (determination of nuclide vectors). Clearance measurement and subsequent statistical analysis are described in Chapter 7 and 8. Chapter 9 provides recommendations for how control programmes should be designed and what information they should include in order to comply with the regulatory requirements in SSMFS 2011:2 (SSM 2011). Chapter 10 provides recommendations for quality assurance, handling of documentation and requirements on competence. The methodology for derivation of clearance levels is described in Chapter 11 and a proposed cost model for calculating costs for a clearance project is presented in Chapter 12.

1.1 Overall requirements

Clearance means that the Nuclear Activities Act and the Radiation Protection Act are no longer applicable for the object that has been cleared. This implies that one of these laws (or both) was previously applicable for the object. Clearance thus differs from the concept of exemption, where an object is excluded from the Radiation Protection Act.

Materials that have or may have been contaminated and/or have been activated in practices involving ionising radiation must initially be regarded as radioactive materials. The responsibility for these materials lies with the licensee according to the Nuclear Activities Act (SFS 1984:3) and the Radiation Protection Act (SFS 1988:220). This responsibility remains until the material has been cleared or the waste has been placed in a final repository that is closed and sealed. In conjunction with decommissioning, it will not be possible to immediately rule out the risk of contamination for some buildings and parts of land. Clearance will be a critical step for these objects, since there is no capacity (in today's Swedish system for management of radioactive waste) for treating soil or entire buildings as radioactive waste.

Clearance is also the endpoint for decommissioning of a nuclear facility. When all radioactive material has been disposed of and all buildings and land have been cleared, the facility itself is cleared. The Nuclear Activities Act and the Radiation Protection Act are then no longer applicable for the facility.

In order to clear an object, it must have been checked for radioactive substances as stated in § 2 SSMFS 2011:2. Furthermore, it requires an assessment of whether the check was adequate and that the presence of radioactive substances do not exceed the levels indicated in SSMFS 2011:2. For buildings, rooms and land, decisions on the clearance are made by the Swedish Radiation Safety Authority (SSM).

1.2 Adaptation of the clearance process

The clearance regulation SSMFS 2011:2 (SSM 2011) applies to all materials, buildings and rooms and all land that may have been contaminated in practices involving ionising radiation. The same set of requirements thereby applies to all objects for which contamination cannot be completely ruled out, regardless of the extent to which the object has been actually contaminated.

For clearance in conjunction with dismantling and demolition of a nuclear facility, however, it is not reasonable nor appropriate to treat all objects in the same way. Objects with known contamination should be managed more rigorously with respect to decontamination and radioactivity checks than objects that have most likely never been contaminated, but for which the risk cannot be completely ruled out. Adaptation of the methods for radioactivity checks with respect to the assessed presence of contamination is supported by recommendations from the IAEA regarding methods for clearance measurements (IAEA 2012), and is an explicit requirement in the regulations (7 § SSMFS 2011:2).

This report therefore proposes that the stages in the clearance process are adapted to the risk categorisation that is described in the Clearance Manual (SKB 2011) and clarified here in Chapter 2, although the actual process is the same for all objects.

2 Clearance during decommissioning

Decommissioning of a nuclear facility requires a number of documents that describe how the decommissioning will be carried out (see Chapter 9 SSMFS 2008:1 (SSM 2008)). In the preparation of these documents, clearance needs to be considered (Figure 2-1). This means that even before the decommissioning phase begins, it is necessary to form an opinion of which objects may be subject to clearance. It should be noted that the initial assessment and some survey measurements will most likely need to be performed before the decommissioning plan, the waste management plan and the sub-project application can be completed.

In conjunction with the planning of decommissioning, sub-projects for decommissioning are identified, which must be reported to SSM before they can begin. When reporting these sub-projects, where clearance is included, the clearance work should be prepared in detail.

2.1 Preparatory measures in different operational phases

This section describes, in general terms, the measures and work operations that should be adopted in different operational phases for a facility, in order to permit effective clearance of the facility in connection with decommissioning.

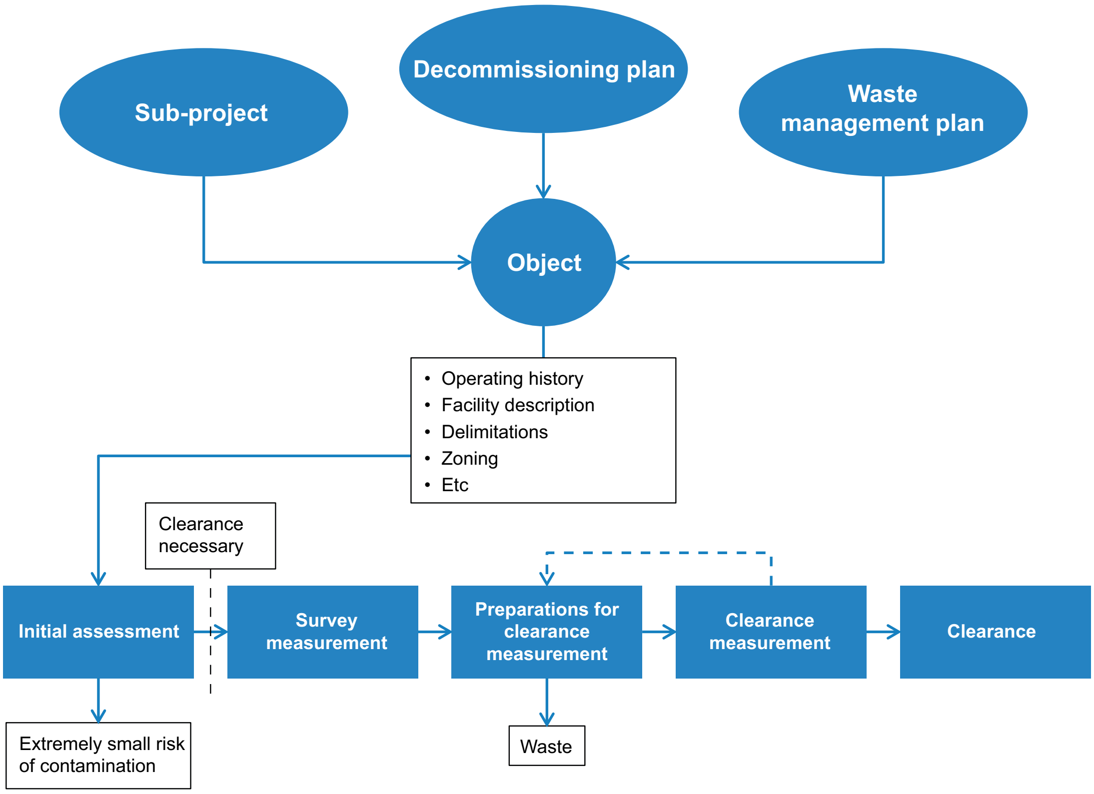


Figure 2-1. *Schematic illustration of the clearance process during decommissioning. When preparing the decommissioning plan, the waste management plan and the description of the decommissioning sub-projects, objects in need of clearance will be identified. The clearance process begins with an initial assessment, which requires detailed information on the object's operating history. After the initial assessment, the object or parts of the object may be excluded from clearance. If clearance is necessary, the clearance process continues with survey measurement, decontamination, clearance measurement and finally a decision on clearance.*

2.1.1 Construction and modification

According to stipulated requirements, decommissioning, where clearance is included, should be taken into account even before a facility is constructed. To facilitate the clearance of a facility, it is advantageous to design the facility with risk categorisation (see Chapter 3) in mind. The facility should be divided into risk categories in advance and be designed so that areas that should be kept free of contamination do not risk being contaminated. If it can be guaranteed during decommissioning that certain parts of the facility cannot have been contaminated, these parts can be decommissioned with no need for clearance.

Clearance should also be considered in conjunction with the selection of materials, for example surface coating that can facilitate/impede clearance and hazardous materials (which may not be disposed of in a final repository). The presence of organic materials can also have a negative impact on the long-term safety of the final repository and may therefore require special measures or clearance.

A description of how the facility is designed with respect to clearance must be documented for a long time and managed so that it is easily available in conjunction with planning of decommissioning. The documentation should also reflect any deviations that arose during the construction phase.

These recommendations should also be considered for modifications of the facility, for example modification or extension.

2.1.2 Operation

Efforts to determine the presence of radioactivity should be initiated as early as possible during the operational phase, at the latest when the date for final shutdown has been determined. At this stage, it is usually time to prepare a detailed plan for the transition period and subsequent dismantling and demolition. For this work, information from the radiological survey has a central role.

The survey information is crucial for determining the extent and approach for decommissioning activities and management of materials and waste. During operation, the radiological survey is often conducted as a combination of an operation-supporting check to ensure the radiological operating environment and a collection of data for future decommissioning.

It is also important that events of importance for clearance and characterisation are documented in a systematic manner (Chapter 9 SSMFS 2008:1 (SSM 2008), IAEA 2002), so that it is guaranteed to be available when the work with the survey prior to clearance begins. If contamination due to, for example, spill is first detected in connection with clearance measurement of activity, it might lead to increased costs and delays in the decommissioning projects.

Deficiencies in the documentation on contamination during operation also makes it difficult to credibly claim that parts of the facility cannot have been contaminated, and therefore may be excluded from clearance.

2.1.3 Transition period

In order for dismantling and demolition to be efficient, the survey should be completed in all areas possible, at the latest by the end of the transition period. Risk categorisation and identification of decontamination needs for surveyed areas should also be completed. Nuclide vectors for clearance and correlation of difficult-to-measure nuclides in waste should also have been determined.

Control programmes for surveyed parts of the facility should be available at the latest by the end of this phase, so that they can be submitted to SSM in conjunction with the sub-project application.

Survey information from operation usually needs to be supplemented in this phase. The new conditions often facilitate survey activities. In addition, some areas will only be available for survey when this phase begins.

The transition period is limited to a few years in the decommissioning plan, but much of the survey work needs to be completed, so as not to delay the subsequent dismantling and demolition. Therefore, as much as possible of the survey and the preparatory work for writing control programmes should be carried out already during operation.

At the latest in this phase, an account according to Article 37 of the Euratom treaty (EU 2010a) should be submitted with information on, for example, clearance levels.

2.1.4 Dismantling and demolition

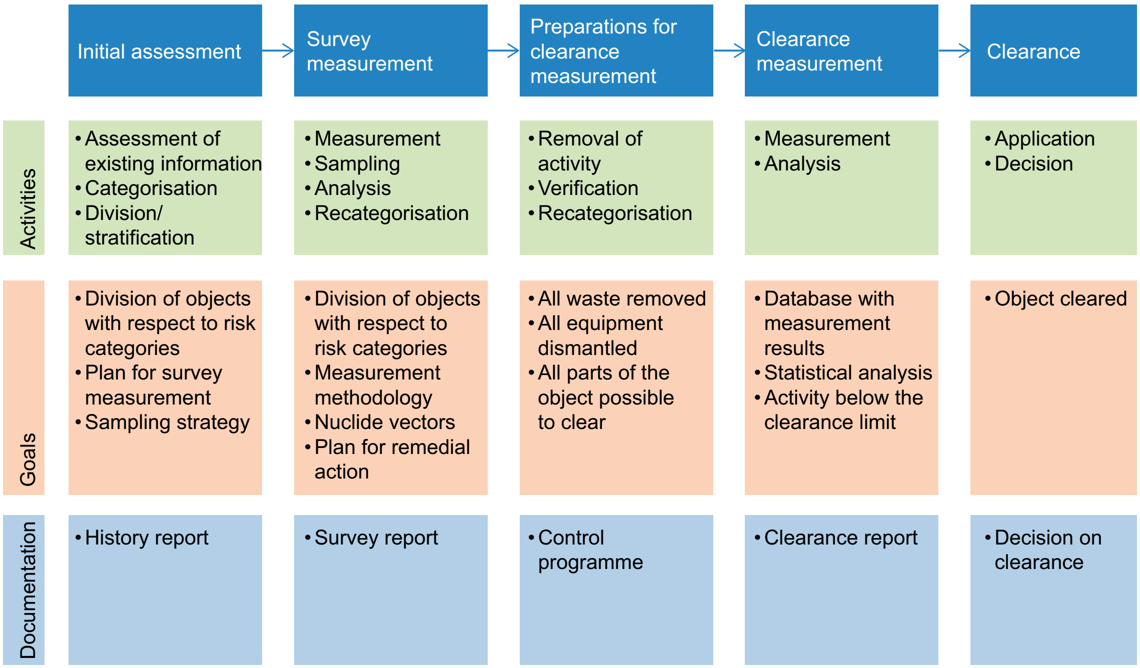
During dismantling and demolition, decontamination and/or clearance measurements for clearance of surveyed objects are carried out. Some parts of the facility will be available for survey only after certain systems are dismantled. Therefore, during this phase, there will be objects or parts of objects in all stages of the clearance process. It will also be important to consider the risk of cross contamination and efficient management of objects in different stages of clearance (surveyed, decontaminated, clearance measured, cleared). This will also affect the logistics of in which order objects will undergo clearance.

During this phase, it will probably be necessary to install new systems for e.g. ventilation and power supply. It is then of great importance that these systems can be cleared easily or be entirely excluded from clearance (extremely small risk of contamination, see Section 3.2.1).

2.2 The clearance process

The stages that must be completed and documented in order for an identified object to be cleared, following a decision by the licensee or in applicable cases SSM, are called the clearance process. This process is described in the Clearance Manual (SKB 2011). The Clearance Manual mainly focuses on materials and small components and is in that respect applicable for clearance in connection with decommissioning. During decommissioning, it will probably be necessary to clear more materials in a shorter time period than during operation, but this does not require any changes to the clearance process.

For buildings, rooms, land and to some extent large components, there is nevertheless reason to clarify the clearance process in order to avoid unnecessary measurements and extended clearance projects. The following is a description of the stages in the clearance process (Figure 2-1) from the time an object is identified as potentially "clearable" (or in need of clearance). Below each stage, the activities that need to be completed in order to proceed to the next stage in the process are presented (Figure 2-2).



	Initial assessment	Survey measurement	Preparations for clearance measurement	Clearance measurement	Clearance
Activities	• Assessment of existing information • Categorisation • Division/ stratification	• Measurement • Sampling • Analysis • Recategorisation	• Removal of activity • Verification • Recategorisation	• Measurement • Analysis	• Application • Decision
Goals	• Division of objects with respect to risk categories • Plan for survey measurement • Sampling strategy	• Division of objects with respect to risk categories • Measurement methodology • Nuclide vectors • Plan for remedial action	• All waste removed • All equipment dismantled • All parts of the object possible to clear	• Database with measurement results • Statistical analysis • Activity below the clearance limit	• Object cleared
Documentation	• History report	• Survey report	• Control programme	• Clearance report	• Decision on clearance

Figure 2-2. *Stages in the clearance process, activities included, goals for each stage and documentation that should be completed within the framework of each stage. The control programme (see Chapter 9) must be completed and submitted to SSM before clearance measurement can commence, but it may be completed earlier than specified in the figure.*

2.2.1 Initial assessment

When an object has been identified, an initial assessment (see further Section 4.2) of the object begins, with the purpose of categorising it according to the risk categories specified in the Clearance Manual:

- Extremely small risk of contamination.
- Small risk of contamination.
- Risk of contamination.
- Contaminated above the clearance limit.

For a complex object (such as a building), it is appropriate to divide it into smaller parts and categorise each part separately. This can be done in different ways, for example by considering physical boundaries between different rooms or by considering how different activities (with different contamination impact) have been separated from each other.

The assessment is based on the documentation available for the object, for example drawings, zoning, operating history. If the object is categorised under *extremely small risk of contamination* (see Section 3.2.1), it does not need to be cleared and can be regarded as conventional. A very limited measurement effort may, however, be needed to verify this (see Chapter 5 in the Clearance Manual).

In other cases, formal clearance must be carried out and a plan for survey measurement (Section 2.2.2) should be prepared as a basis for the next stage. It should contain

- a division of the object into areas according to the presence of contamination, so that the contamination level can be assumed to be homogeneous in each area,
- a sampling strategy for survey measurements (including background measurements) and sampling for determination of nuclide vectors (see Chapter 6),
- the choice of measurement method and calibration method (see Section 4.2.3).

In order to select a measurement method, an initial assessment of occurring nuclides should be made. Although the main purpose of survey measurement is to identify potential areas with contamination, it may still be useful to include the results of the radiological survey when the results of clearance measurements are analysed. It can therefore be a good idea, in this stage, to also begin to draw up a control programme for subsequent clearance measurement (see Chapter 9).

2.2.2 Survey measurement

This stage can be said to be the starting point for formal clearance. From this point, it is difficult to credibly categorise an object under *extremely small risk of contamination* (unless previous historical information is found to be inaccurate). The object must therefore, from this point onwards, be subject to clearance or managed as radioactive waste. Survey measurement is described in greater detail in Section 4.3.

The radiological survey aims to provide a detailed picture of the degree of contamination (and activation, where applicable), and how it is distributed over the object, so that any decontamination measures can be carried out before clearance measurement. In connection with clearance, the goal is to, with limited effort, minimise the risk that contamination above the clearance level is first detected in connection with clearance measurement, since the measurements must then be interrupted for removal of activity in the contaminated areas.

In conjunction with the radiological survey, it can also be appropriate to determine the nuclide composition of the contamination. Alternatively, this can be done in conjunction with decontamination. The results of survey measurements should serve as a basis for

- initial assessment of the contamination level for each subarea of the object,
- determination of nuclide vectors for assessment of nuclide-specific activity (see Chapter 6),
- updated division of the object with respect to subareas (see 2.2.1),
- updated categorisation of each subarea of the object,

- choice of decontamination measures (method, extent, etc. see Chapter 5),
- choice of method for clearance measurement,
- assessment of the potential for clearance using regulatory or in other ways stipulated clearance levels.

After the radiological survey, all parts of the object should be able to undergo clearance measurement, if they have not been found to be contaminated above the clearance level. In conjunction with this, a decision should be made on whether the object can be cleared with current clearance levels. The results of the survey should be documented in a specific report.

2.2.3 Preparations for clearance measurement

In this stage, all measures that are required to remove radioactivity from contaminated parts of the object are carried out, so that all parts of the object can be cleared after clearance measurement. Unless nuclide vectors have been determined in previous stages, an analysis of the nuclide composition must be conducted in conjunction with this stage (for example in conjunction with decontamination). The steps that should be performed or updated are:

- Decontamination (see Chapter 5).
- Division of the object so that each subarea can be regarded as homogeneous with respect to presence of radioactivity.
- Determination of nuclide vectors for clearance (see Chapter 6).
- Completion (unless carried out previously) and submission of the control programme (see Chapter 9).

2.2.4 Clearance measurement

In this stage, clearance measurement (Chapter 7) is performed according to the control programme. All measurement data should be stored in a quality assured manner. A statistical analysis (Chapter 8) and evaluation of measurement data should be documented in a report, that will then serve as a basis for decisions on clearance. The report should also describe the implementation of checks for radioactivity and thereby show that the control programme has been followed.

Decision on or application for clearance

If the object is considered to be material, in the last stage, a formal decision on clearance is made by the licensee. For buildings that will be sold or demolished and for land a decision by SSM is required. Buildings and rooms that meet the requirements for clearance can be used for other purposes within the licensee's activities, without a decision on clearance.

The application for clearance to SSM is sent as a formal letter, where a report from the clearance measurement and subsequent analysis of data is attached.

2.3 Derivation of clearance levels

In some cases it may be necessary to apply for clearance of one or several objects with other clearance levels than those specified in SSMFS 2011:2 (SSM 2011). This approach is also used for clearance of land.

When it comes to clearance of land, it should be possible to derive clearance levels when the final state of the facility and the future use of the site have been determined.

The work with derivation of clearance levels (Chapter 11) for land should take place in parallel with the development of a complete decommissioning plan, so that the consequences for the chosen final state of the site are clear. In this process, it is important to involve other stakeholders, such as the municipality and county administrative board.

When defining scenarios and the final state, an analysis of a suitable reference object should be included. The reference object should represent the original (before construction of the facility) radiological conditions. Guidelines for determining these are provided by the IAEA (2014b). The guidelines suggest that a similar, but unaffected, area can serve as a reference object in cases where the site's original radiological conditions are unknown.

In conjunction with the development of material for the account according to Article 37 of the Euratom treaty (EU 2010a), clearance levels should be presented. However, this does not apply to clearance levels for land, since they are not normally judged to affect any other countries in the EU (EU 2010b, Appendix 5.4).

As mentioned above, in some cases it may be necessary to apply for clearance with other levels than those prescribed. If so, it is likely that this situation arises in conjunction with the radiological survey, if it turns out that an object cannot (with reasonable efforts) be cleared according to prescribed levels, but that the alternative, to consider the entire object as radioactive waste, is unmanageable. Other alternatives must then be evaluated.

2.4 Summary

The different stages in the clearance process require extensive preparations in order to be implemented efficiently. This means that much of the preparations must be carried out during a time when the facility is still in operation. In order to limit the extent of the clearance work, it is also important that the documentation of the facility with respect to the presence of contamination is complete and easily available in the planning phase prior to a clearance project. If the documentation is inadequate or inaccurate, it will be difficult to categorise objects under the risk category *extremely small risk of contamination* (see Section 3.2.1), which in turn leads to more objects needing to go through all the stages in the clearance process before demolition.

3 Risk categorisation

A nuclear facility often has large variations in the degree of radioactive contamination. Large parts of the facility are located outside the controlled and from a radiological perspective protected area. With fully functioning barriers, radioactive contamination should not occur outside the controlled area. Since most facilities have handled radioactive material on a radiation protected area, there is, however, an obvious risk that small quantities of radioactivity could have been released and thereby contaminated materials, rooms or land. History also shows that radioactive contamination has been detected in, for example, break rooms, workshops, outside gates, outside changing rooms, in temporary storage areas etc. In most cases, the radioactivity has been below the clearance limit.

In order to achieve systematic management of clearance, adapted to the risk of contamination, a system for categorisation of radioactive contamination has been developed in the Swedish nuclear industry, which is described in greater detail in section 3.2 below and in the Clearance Manual (SKB 2011). The concept of *risk* is used here in the same way as in the Clearance Manual, even though it is actually a question of the *probability* of contamination rather than risk.

3.1 Categorisation in the different phases for a facility

During operation, there is some categorisation in the nuclear facilities through the division into controlled area, radiation protected area and other areas. There are no radiological activities in other areas. However, shipments of contaminated material or equipment may have passed through these areas. In some cases, e.g. final inspection of emptied and cleaned transport containers is done outside the protected area.

Controlled areas are usually divided into several categories (for example white, blue, yellow or red) from several aspects (for example airborne contamination, surface contamination and external radiation).

This division is not sufficient in a decommissioning context. Decommissioning requires a finer division, especially for the lower levels, at the same time as it is important to find out and describe how the situation actually is and not how it should be. In for example workshops, repair of material that have been in controlled areas (which has been cleaned and cleared) can over time build up a radiological inventory to the extent that it cannot be ruled out that it might exceed the clearance limit.

Somewhat simplified, it is in conjunction with the radiological survey that a facility or an object is categorised, since it is then the actual conditions are investigated.

In practice, a facility or an object needs to be categorised even before or in connection with the planning of the survey. To survey an entire facility in the same way is not particularly efficient and probably a lot more expensive than adapting the survey based on the risk and degree of radioactive contamination. To only survey the controlled area (and thereby declare other areas to be without risk of radioactive contamination) is not in line with neither good practice nor the applicable regulatory framework.

3.2 Division and principles

The following categories are used in the clearance context:

- Extremely small risk of contamination.
- Small risk of contamination.
- Risk of contamination.
- Contamination above the clearance limit.

The jointly defined categories are described below. By using these categories during the stages of the clearance process, work can be adapted in order to be as efficient as possible. The clearance measurements also need to be adapted to each category, see further Chapter 7.

3.2.1 Extremely small risk of contamination

Materials, rooms, buildings and land where no radioactive material has been handled and no contamination has been historically detected, which thus cannot reasonably have been contaminated with radioactive substances, can be categorised under *extremely small risk of contamination*.

For this category, it is not necessary to complete a measurement programme for clearance under normal circumstances. Thus, there is no reason to carry out survey measurements either. The categorisation is based on other assessments such as descriptions of the activities that have been carried out and other historical information.

Materials, rooms, buildings and land with extremely small risk are actually outside the scope of what is covered in the clearance regulation. No formal clearance is needed for this category, however, it requires an assessment of whether the categorisation is correct.

Examples of materials are:

- All materials outside the controlled area that cannot reasonably have been subjected to any radioactive contamination.
- Materials from the radiation protected area that with great certainty cannot have been subjected to any radioactive contamination.

Examples of buildings and rooms are:

- All buildings and rooms outside the controlled area that cannot reasonably have been subjected to any radioactive contamination.
- Buildings and rooms within the radiation protected area that with great certainty cannot have been subjected to any radioactive contamination, for example an electrical room with a separate entrance.

Examples of land are:

- All areas outside the controlled area that cannot reasonably have been subjected to any radioactive contamination.
- Areas within the radiation protected area that with great certainty cannot have been subjected to any radioactive contamination, for example green spaces that have never been used as storage areas etc.

No materials and no rooms, buildings or outdoor spaces within the controlled (with respect to contamination) area should be categorised under *extremely small risk of contamination*.

3.2.2 Small risk of contamination

The category *small risk of contamination* includes materials, rooms, buildings and land that may have been contaminated with radioactive substances, but that nevertheless on good grounds can be assumed to be free from radioactive contamination, or to be clearable with a good margin to regulatory limits without any special measures (for example decontamination).

For the category *small risk of contamination*, a radiological survey with some verified measurements may need to be carried out. Materials, rooms, buildings and land with *small risk of contamination* must be formally cleared.

The extent of the measurement programme is adapted to the risk of contamination and can therefore consist of sampling and/or scanning.

If activity close to current limits is measured, or if there is a need for decontamination prior to clearance, the object should unconditionally be recategorised under *risk of contamination* or *contamination above the clearance limit.*

Examples of materials are:

- Materials outside the controlled area that could, but (naturally) should not have been subjected to any radioactive contamination, for example equipment in the clean side of changing rooms, furnishings in offices and break rooms in connection to the controlled area.

- Materials from the radiation protected area that should not have been subjected to any radioactive contamination.
- Materials from the controlled area that with good certainty have not been exposed to any radioactive contamination of importance in a clearance context.

Examples of buildings and rooms are:

- Buildings and rooms outside the controlled area that may have been exposed to radioactive contamination or where there is a risk that surfaces in the rooms have built up radioactive contamination over time.
- Buildings and rooms within the radiation protected area where only packaged radioactive material, or unshielded materials with a surface contamination below applicable limits for surface contamination, have been handled.
- Rooms within the controlled area where no radiological activities have been conducted, no personnel from radiological activities have passed through and that has not reasonably been exposed to any airborne contamination. For this category, good facility knowledge over time is important.

Examples of land are:

- Other areas outside the controlled area, i.e. those that are not categorised under extremely small risk (if there are areas outside the controlled area with a risk of contamination, they should be classified as radiation protected areas).
- Areas within the radiation protected area where packaged radioactive material, or unshielded materials with a surface contamination below applicable limits for surface contamination, have been handled.
- Outdoor spaces within the controlled area where only packaged radioactive material, or unshielded materials with a surface contamination below applicable limits for surface contamination, have been handled.

3.2.3 Risk of contamination

The category *risk of contamination* includes materials, rooms, buildings and land that, as a result of conducted activities or handling, can be assumed to be contaminated with radioactive substances. In many cases, decontamination measures must be taken before clearance. For the assessment of risk, a radiological survey should be carried out. Materials, rooms, buildings and land with *risk of contamination* must be formally cleared.

Examples of materials are:

- Materials from the radiation protected area where surface-contaminated or potentially surface-contaminated materials have been handled or stored to such an extent, that it cannot be ruled out that the materials, for example tools and handling equipment, will exceed the clearance limit.
- All other material from the controlled area that has not already been found to be contaminated or have a radioactive content above the clearance limit.

Examples of buildings and rooms are:

- Buildings and rooms within the radiation protected area where surface-contaminated or potentially surface-contaminated material has been handled or stored to such an extent, that it cannot be ruled out that they will exceed the clearance limit.
- all other buildings and rooms within the controlled area that have not already been identified as contaminated above the clearance limit.

Examples of land are:

- Areas within the radiation protected area where surface-contaminated or potentially surface-contaminated material has been handled or stored to such an extent, that it cannot be ruled out that they will exceed the clearance limit.
- All other areas within the controlled area.

No material and no rooms, buildings or outdoor surfaces outside the controlled area should normally be categorised under *risk of contamination*.

3.2.4 Contamination above the clearance limit

In the context of surveys, at least one additional category is often used, namely materials, rooms, buildings and land with radioactive contamination above the clearance limit.

For this category, the main question is whether it is necessary/possible to carry out decontamination or if the object in its entirety should be considered as radioactive material or waste. For rooms, buildings and land, it is a question of which measures are required to meet the criteria for clearance. This can be done by for example cleaning or removal of surface layers (see Chapter 5).

Clearance measurement is not necessary until after the requisite decontamination (if possible), when clearance measurements can be conducted in accordance with the category *risk of contamination*.

3.3 Recategorisation during clearance

Some objects or parts of objects will have to be recategorised during the clearance process, when new information becomes available or measures are taken to remove contamination. Recategorisation can take place at any time, but it must be documented and justified in a traceable way, since the remaining stages in the clearance process are dependent on the object's risk categorisation. On two occasions in the process, recategorisation should always be done:

- After completed radiological survey when the object's radiological status is known in detail.
- After decontamination when the object's radiological status has changed.

The following principles should be used for recategorisation:

- Extremely small risk of contamination – If information emerges with the result that contamination cannot be ruled out or if contamination is detected, the object shall be recategorised according to the risk of occurrence of contamination.
- Small risk of contamination – If the survey does not show any presence of contamination, the object remains in this risk category. If contamination is detected, the object should be recategorised according to the risk for occurrence of contamination.
- Risk of contamination – If the survey does not show any presence of contamination, the object can be recategorised to small risk of contamination. If contamination above the clearance limit is detected, the object should be recategorised to contamination above the clearance limit.
- Contamination above the clearance limit – After decontamination (and verification), the object can be categorised under *risk of contamination*.

It is important that recategorisation as a result of measured activity is adapted to the risk of contamination *above* the clearance level. If it is possible to assess the uncertainty in the measurement data, this risk can be quantified as in Section 8.6. It is also necessary to assess how the contamination is distributed over the surface of the object and, based on some method of interpolation, judge whether there may be contamination above the clearance limit in any point that was not subject to survey measurement.

Recategorisation of objects from a higher risk category to *extremely small risk of contamination* cannot be based on measurement results or decontamination measures. It is not possible to claim *extremely small risk*, if contamination could not be ruled out based on operating history earlier in the process. However, during the process it may turn out that the historical information used in the initial assessment was inadequate or inaccurate. If this has led to an incorrect categorisation of an object, the categorisation could be revised based on correct and complete information. It may then be necessary to recategorise an object to *extremely small risk of contamination*.

4 Radiological survey

The term radiological survey can be summarised as a status assessment from a radiological point of view. The purpose of the survey is partly to verify the initial categorisation, but predominantly to get an overview of the presence of radioactive contamination from several aspects such as its type, form, extent and concentration. The radiological survey is one of the most important cornerstones in a decommissioning project and constitutes the basis for

- choice of measurement method for clearance measurement,
- determination of nuclide vectors,
- delimitation and risk categorisation of facility areas (i.e. surfaces) prior to clearance measurement.

A radiological survey often entails extensive work where large quantities of data is collected, generated (by measurement) and compiled. Therefore, thorough planning and systematic storage and processing of data are extremely important in order to ensure that the extensive work effort also provides the information needed to proceed in the clearance process and the entire decommissioning. If managed correctly, these data can also be used as a complement to clearance measurements.

In an ideal scenario, planning for decommissioning of a nuclear facility starts before the facility is constructed (see Section 2.1.1). Thereafter, various types of survey activities are conducted during the entire life cycle of the facility. The content and intensity of the investigations change with the phases of the facility. Radiological survey activities are conducted in some form up until the decommissioning has been completed and the facility is no longer subject to the nuclear regulatory framework.

A common misunderstanding is that radiological survey only concerns measurements, samples and radiological analyses. The truth is that operating history, incident reports, knowledge of changed activities, facility modifications etc. are equally important parameters in a radiological survey.

Another common misunderstanding is that the results from a radiological survey also constitute a complete basis for clearance. Some information can typically be used as a basis for clearance provided that quality criteria, traceability, etc. are met. Normally, however, a radiological survey is considerably less detailed than what is needed for clearance, since a radiological survey and clearance measurements prior to clearance have different purposes. The results of the survey should give an overview of a facility's radiological status while the clearance measurements should ensure that applicable limits are met.

As soon as decommissioning of a nuclear facility is planned or decided, planning of the survey must begin/be intensified.

Survey planning should include

- developing a set of requirements for the survey,
- an analysis of how the survey project's needs are implemented as practical measures (needs analysis, see Section 4.1.1),
- what principles and goals are needed (purpose),
- an inventory of the methods and measures required to complete the survey,
- the choice of information management tools and quality assurance systems.

The implementation of systems and procedures for ensuring traceability and quality assurance must be given priority. Far too many survey projects have been forced to discard large quantities of information due to deficiencies in quality assurance and traceability.

4.1 Initiation

Before a radiological survey is initiated, it is important to establish the needs and goals for collection of information. The initiation phase therefore consists of an identification of the purpose and principal goal of the efforts, and should be documented in a technical report containing

- purpose and goals,
- conditions – a brief description of the objects and/or facility parts that will be surveyed,
- identified needs (see Section 4.1.1 below),
- initial risk categorisation insofar as it exists (see Section 4.2 below),
- available data, other available information,
- the types of survey activities expected,
- adaptation to the statistical model that will be used.

It is crucial to define which information is required and what requirements are made on accuracy. Survey activities are expensive and usually have relatively long lead times from initiation until the final report is produced. To a large extent, the radiological survey is a prerequisite for subsequent activities. An insufficient or incorrectly performed radiological survey, caused by inadequate needs analysis or inaccurate initial facility categorisation, could have serious consequences for a decommissioning project.

4.1.1 Needs analysis

A needs analysis regarding the type of information that should be collected, the degree of detail (detection limits, number of measurement points per unit area, etc.) and delimitations, must be carried out to ensure that the survey achieves established or likely goals. It is recommended to use an established methodology to conduct the needs analysis.

The USA's federal environmental authority, the U.S. EPA, has developed the following method for needs analysis (see for example EPA 2006a, MARSSIM (NRC 2000) or MARLAP (NRC 2004)). This methodology, often called the *DQO process* (Data Quality Objectives), has been implemented and used in a number of countries. The methodology consists of seven steps developed to define clear survey goals:

1. *Describe the problem*
   Describe the question that the survey should answer clearly. Utilise experience from previous surveys (for both the own facility and other similar facilities). Create an understanding of the question.
2. *Identify the goal of the project*
   List the questions to be answered and the actions and decisions that may be required for this.
3. *Identify the input data required to answer the questions*
   Identify what information must be gathered to create conditions for answering the questions and choose suitable methods for collecting and analysing data.
4. *Define the outer limits of the project*
   Define boundaries for the survey efforts with respect to execution time and physical limitations. Determine when and where the information should be gathered.
5. *Develop a decision model*
   Define which parameters and criteria are of importance and their requirements. They will then be used as criteria for the survey's measurement and analysis efforts.
6. *Formulate acceptance criteria*
   Define acceptance criteria for information and conclusions in the survey, based on the consequences of an incorrect decision due to inadequate information. This assessment can concern the number of samples (i.e. how fine-grained the study is), selected measurement methods, detection limits, which nuclides are measured, etc.
7. *Optimise the survey project*
   Evaluate information from previous surveys of the facility and prepare alternative data collection models. Choose the most efficient methods or combination of methods that satisfy stipulated requirements. It is important that the gathered information is representative, in line with established goals and sufficiently complete.

4.1.2 Goals and purpose

The goals and purpose of survey activities may vary, but when it comes to surveys in order to clear and demolish a facility, the overall goal is to produce the information needed for subsequent stages in the process, normally clearance measurement or decontamination (when objects cannot be categorised under *extremely small risk of contamination*). The radiological survey should then include

- determination of the radioactive contamination's form, extent and variation,
- verification of the facility's theoretical activation and contamination calculations,
- determination and/or verification of nuclide vectors.

In addition to providing an overview of the facility's radiological status, the radiological survey should produce information as a basis for

- assessing requisite decontamination, both suitable methods and extent,
- quantifying the need for waste management, waste treatment and final disposal,
- determining what restoration efforts are needed in the later phases of decommissioning (potential revision of the decommissioning plan),
- assessing the dose to decommissioning personnel and the risk of releases as well as the need for remote handling, ventilation and personal protective equipment,
- preparing safety analysis reports, environmental impact statements, cost calculations, accounts according to article 37 (EU 2010a), etc.

4.2 Initial assessment and planning

4.2.1 Existing information

Quality assured existing information concerning the facility is a great asset for a survey project. A well balanced use of existing information in the continued work, both measurement data and other information, may entail great savings in terms of resources, as well as the number of measurements and analyses.

It should be noted that historical information is not always to the advantage of a survey project. Incorrect, exaggerated or inadequate information may entail unnecessarily extensive efforts in order to, for example, identify radiological consequences of an incident. A thorough evaluation of collected historical information in an early phase is recommended.

Information that needs to be gathered is, for example, drawings and descriptions of the facility as-built, i.e. as the facility is actually constructed (which may differ from the drawings), as well as information on zoning and any previous risk categorisation. In order to get as good a description of the operating history as possible, previous activities should be described in as much detail as possible. The description should answer the following questions:

- Has water- or airborne contamination occurred in the object (leakage in active areas)?
- Where have contaminated materials been handled/stored?
- Where have known contamination incidents occurred (leakage in for example tank cells)?
- How could the contamination have spread (for example with personnel)?
- What maintenance measures have been carried out?
- Are there environmentally hazardous materials (hazardous materials and health and safety risks should also be identified)?
- Could the contamination be related to external influences or activities that occurred on the site before the facility was commissioned?

It cannot be assumed that all events of importance for clearance have been documented so that the information is easily available. Therefore, if possible, interviews should be conducted with operative personnel in order to get as good a picture of the facility's history as possible.

The following points need to be taken into particular consideration when it comes to existing/historical information:

- Identify areas that deviate from the norm (due to for example spill or historical activities that have affected the radiological environment), and thus warrant extra attention in conjunction with the survey.
- Describe historical events and previous activities in a structured and detailed manner (for example date or time period, site, activity/incident description etc.), including relevant reference material.
- Address areas where there are inconsistencies or gaps in the available information.

Well-structured management of existing information can create opportunities for

- more targeted efforts during the survey and the rest of decommissioning,
- lower costs (by avoiding new collection of already existing data),
- reducing the risk of an inadequate/incomplete survey.

4.2.2 Initial assessment

The purpose of the initial assessment is primarily to make a risk categorisation of the object. Further survey work is then adapted to this risk categorisation.

It is very important that a facility under decommissioning, as early as possible is categorised according to the risk categories described above in Chapter 3. If the initial risk categorisation cannot be retrieved directly from existing documentation, the historical information (according to Section 4.2.1) should serve as a basis for a first risk categorisation.

For a facility in operation, the categorisation is highly preliminary for natural reasons, but still of great importance both for planning of survey efforts and for decommissioning planning in general. An initial categorisation can also help facilities in operation to avoid that contaminated material is brought into areas that have been categorised as clean.

An inadequate or incorrectly performed initial facility categorisation can, in the worst case, lead to an insufficient survey and that radioactive contaminated material is later transported out of the facility by mistake.

If the initial categorisation is too conservative, it may entail that unnecessary resources are spent on radiological survey of completely clean facility parts.

It is therefore of great importance that the initial risk categorisation is made carefully. In this stage, the category *extremely small risk of contamination* can be applied for the parts of the facility where it is safe to say, based on the existing information on the facility, that contamination does not occur (see Chapter 3).

In addition to this risk categorisation, during the initial assessment the information that is required to plan and perform survey measurements and decontamination should be gathered. The information that should be produced in this phase is

- the desired final state of the site and future activities at the site (applies above all to land),
- a 3D model to create a sampling plan and analyse measurement data,
- theoretical assessment of potentially occurring nuclides and calculation of nuclide vectors,
- suitable decontamination methods for handling
  - loose contamination,
  - locally penetrated contamination (for example fractures and interfaces),
  - fixed or homogeneously penetrated contamination or activation.

4.2.3 Choice of measurement methods for survey measurements

A part of the purpose of the survey is to determine a suitable measurement method for clearance measurements. In conjunction with survey measurements, it is not certain that all factors that affect the choice of measurement method are known. The choice of measurement methods for survey measurements must therefore be based on existing information on the facility as well as experience from previous survey activities.

The choice of method for survey measurements is greatly affected by the type of radioactive contamination and the contamination properties:

- The presence of substantial alpha- and pure beta-emitting contamination requires sampling and subsequent laboratory analyses for nuclide-specific determination of activity.
- Highly heterogeneous contamination increases the need for sampling to determine the nuclide composition.
- Contamination that has penetrated into the matrix, for example contamination of concrete structures, requires sampling.
- Activated material also requires sampling to determine the depth of activation and nuclide distribution.
- Other types of contamination, for example purely shallow contamination on metallic surfaces or other building surfaces with insignificant risk for penetration of radioactivity, can often be determined by field measurements, provided that the background level does not cause disturbances.

It should be tried to combine measurement methods that cover a large area (for example gamma spectroscopy measurement with an unshielded detector or dose rate measurement) with methods that provide detailed local information about the contamination (count rate measurement or gamma spectroscopy measurement of a small surface). Thereby, it is possible to get an overview of both the average contamination level and the contamination's spatial distribution.

Based on the initial assessment of the presence of radioactivity, distribution and nuclide vectors, the following steps should be carried out:

- Identify suitable measurement methods for determining activity with scintillation equipment and gamma spectroscopy (which most likely can also be used for clearance measurement).
- Identify difficult-to-measure nuclides for *ex situ* analysis.
- Identify quality assured methods for *ex situ* analyses or identify suppliers that can perform these analyses (for example by accreditation).

4.2.4 Sampling strategy for survey measurements

The purpose of developing a sampling strategy is to establish principles and guidelines for the implementation phase in order to ensure that sufficient and appropriate information is collected. For example:

- approaches considering physical, radiological and temporal limitations,
- requirements on procedures to ensure that quality objectives and traceability can be achieved,
- principles for management of data and other information, as well as statistical models for evaluation.

During the survey, it is not necessary to ensure that statistical methods are applicable in the same way as during clearance measurements. Measurement points can thus be distributed to cover the surfaces of objects as well as possible or to focus sampling efforts in order to identify and delineate contaminated areas. The methodology that is employed for analysing the contamination's spatial distribution (for example *kriging*[1]) can, however, impose requirements on the distribution of measurement and sample points (OECD/NEA 2013).

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[1] Kriging is a statistical method for interpolation.

The strategy for sampling and measurement can either be based on assessment or probability. Probabilistic methods require no direct knowledge of the facility, since the measurement points are chosen randomly or distributed according to a certain scheme (for example in a grid). The probability of radioactive contamination is not a criterion for the location of measurement and sampling points. Because the purpose of survey measurements is mainly to localise and determine the extent of potential contamination, an approach based on assessment can limit the sampling to areas where the probability of contamination is judged to be highest. In this way, the costs for sampling, analysis and measurement can be minimised, but it requires very good knowledge of the facility. Otherwise, there is a great risk of missing contaminated areas that will only be detected in connection with clearance measurements.

In complex situations, a combination of assessment-based and probabilistic methods may be preferable. The requirements for clearance measurement (Chapter 7) should also be taken into account, so that data from the survey can be reused.

In order to implement the strategy chosen for sampling and direct measurements, a plan is needed. Such a plan should contain

- an introduction describing the object, the problem behind the survey and the purpose/goal of the project,
- a summary of the sampling and measurement strategy, including the actual strategy but also an overview of the considerations that have been made,
- a description of how the strategy is implemented in practical measures,
- distribution of measurement and sampling points,
- a description of measurement techniques and acceptance criteria,
- instructions for management of samples, measurement data and other information,
- instructions and requirements for field measurements (including function checks and calibration),
- procedures for information management and analysis of data.

The last point also includes systems for registration and storage of measurement data, including position information.

4.2.5 Documentation and plan

The results from the initial assessment and the preparatory steps prior to survey measurements should be reported in a history report. The intention is not to produce new information to fill obvious gaps, inconsistencies and other deficiencies in the available information. Deficiencies should instead be identified and noted as a basis for decisions on actions. The report should also clearly describe what evaluation has been made of the existing/historical information.

The document should be based on a critical assessment of relevant information, whose quantity and quality varies depending on the original purpose of the historical documentation.

The report should include

- a descriptionof the division into subareas according to risk categories,
- risk categories for each subarea and justification of these,
- a descriptionof the estimated nuclide-specific presence of radioactivity,
- a descriptionof proposed measurement methods and the extent of measurements,
- recommendations and conclusions for continued work.

The sampling plan is preferably documented in the same system that is used for planning the measurements, registration of measurement data and analysis of measured values.

When the initial assessment is concluded, updates should be made to the project plan, cost calculation and project organisation for the continued work.

4.3 Survey measurement

4.3.1 Sampling and measurement

The process for sampling and measurement consists of three parts:

1. Preparations – understanding of the sampling plan, development of operative instructions, development of sampling and measurement equipment, preparation of the sampling object. The preparations should include ensuring the calibration of monitoring equipment, function checks and, not least, training of personnel.
2. Execution – sampling, field measurements, radiation protection and conventional safety, inspection and handling of sample containers, documentation of the actions performed.
3. Delivery – dispatch of samples to the analysis laboratory, management of sample results and archiving of sample material.

Common errors in conjunction with sampling are for example

- incorrect preparations,
- unsuitable choice or use of sampling tools,
- uncalibrated equipment,
- inadequate or incorrect vessel for samples,
- faulty sample composition or sampling,
- incorrect ambient value (measurement environment),
- changed conditions (weather, temperature),
- loss of sample material (for example volatile elements),
- cross contamination,
- sampling at the wrong position or incorrect registration of position,
- inadequate or faulty labelling of samples.

For more examples of potential errors in sampling and sample handling see for example MARLAP (NRC 2004).

4.3.2 Measurement methods for radiological survey

Typical field measurements are dose rate and count rate measurements and nuclide-specific gamma measurements.

Dose rate measurements are used as a first indication of radioactive content and are conducted according to standard radiation protection procedures, primarily in areas that contain radioactive systems or system parts. It is not possible to determine whether a material or a surface is subject to clearance or not with a dose rate instrument, which is why dose rate measurement at very low dose rates needs to be supplemented with count rate measurement to be of greater value for a radiological survey.

Count rate measurement with a scintillation detector gives a good indication of the total activity level for beta- and (depending on the choice of detector) gamma-emitting nuclides. Alpha-emitting nuclides can also be determined but there is a great risk of shielding if the surfaces have any coating or, for example, have been repainted. It is important to mention that low-emitting nuclides, such as nickel isotopes Ni-59 and Ni-63, cannot be detected with a scintillation detector. If, and if so to what extent, low-emitting nuclides may occur in such concentrations that they need to be determined, should be assessed in the planning phase since they have a great impact on the requirements and costs for laboratory analyses.

Nuclide-specific field measurement of gamma-emitting nuclides with a germanium detector or a sodium iodide detector is an effective method for determining the activity for larger surfaces. Alternatively, a gamma camera (see for example Carrel et al. 2011) can be used for field measurements (more examples of measurement and sampling equipment is provided in Appendix B).

Laboratory-analysed material samples should serve as a basis for determination of the nuclide vector. The nuclide vector can in turn provide a scintillation efficiency, if scintillation efficiency measurements cannot be conducted for practical reasons.

Background radiation (for example K-40 in concrete) needs to be considered in all field measurements, and can be handled by for example a separate determination of the background level or background correction based on analysis of gamma spectrum (Gilmore 2008).

Somewhat simplified, sampling supplemented by laboratory analyses can be divided into smear tests and material sample analysis. These methods include simple analyses such as smear tests combined with *in situ* analysis of total activity , as well as material samples, which are sent to special laboratories for determination of low-emitting nuclides such as C-14 and Cl-36.

Smear tests are a simple but unreliable method for determination of radioactivity. Put simply, smear tests give an indication of the amount of loose radioactivity. Smear samples can, if required, be analysed on a nuclide-specific basis. Smear samples, however, give no indication of fixed radioactive contamination. Despite their limitations smear tests are, because of their simplicity, an important and appreciated measurement method for radiological survey. A radiological survey conducted solely by means of smear tests, however, provides very limited and unreliable results.

As a complement to smear test sampling, sweeping of larger areas of the surface can be conducted in order to provide a general overview of the contamination. Smear tests using tape or a similar sampling material can also be an alternative for areas not suitable for standard smear tests (such as concrete surfaces).

Determination of fixed nuclides is made by analysis of material samples. Samples are measured in their entirety (nuclide-specific gamma measurement) or a small subset of the samples are prepared for analysis (nuclide-specific alpha or beta measurement). Nuclide-specific analysis of material samples is particularly important in the determination of nuclide vectors (see Chapter 6)

4.3.3 Analysis and evaluation

The laboratories where analyses of the samples are performed must meet stipulated requirements on quality assurance (see Chapter 10). Deficiencies in quality assurance reduce or, in the worst case, eliminate the value of the analysis results.

Supplementary quality assurance measures, such as double analyses for a subset of samples, can be carried out as a part of quality assurance. Data from the double samples can be used in several ways, for example to identify deviations, trends or patterns of interest, and not least the uncertainty in the analyses.

Many samples taken for the radiological survey can also be useful for determining the presence of radioactivity in other parts of a facility. Information on nuclide composition can, for example, be used for determination of nuclide vectors for objects with a similar contamination history.

Efficient and reliable processing of data in conjunction with radiological survey is extremely important. The development of a system for managing the information that is gathered in a survey project should be given priority early in the planning phase. There are commercial systems on the market which will likely need to be adapted to the specific need. A clear requirements specification needs to be prepared before proceeding with the evaluation and choice of system. Before sampling and measurements begin, the system for collecting and systematising data must be tested and quality assured (examples of data management systems are given in Appendix C).

Data management means, among other things, assessment and evaluation of the data generated in field measurements and laboratory analyses, with the purpose of ensuring usefulness, quality and that overall goals are met.

A preliminary assessment of obtained measurement data should be made as soon as possible. Early discovery of individual or systematic deficiencies reduces the consequences. For example, sample material may still be in the laboratory, measurement and sampling personnel with equipment are available for both determining the cause and to take compensatory measures. Early discovery reduces the risk of increased costs and delays in the project.

If a set of data is identified as unusable or deviant, the deficiency should be followed up formally with those involved. This provides the conditions for a quick remediation and information for trend and performance tracing of equipment, measurement teams, analysis laboratory etc.

If an information item is judged to be complete and without unacceptable deficiencies in the preliminary assessment, it should be registered in the information management system. If data from previous measurements are already registered in the system, it is important that there is a formal step where someone assesses the information and approves it for use in the radiological survey. This step needs to be documented.

Statistical or automated methods can be used for assessment of data but they cannot fully replace manual assessment.

The process for inspection and approval of data needs to be effective, since it normally involves large quantities of data. The consequences of late discovery of deficiencies due to delay could be large. The necessary competence for reviewers should be in proportion to the complexity and importance of the information.

Unexpected or deviant results should be manageable in the survey, but the DQO process (see Section 4.1.1) may need to be updated to take the unexpected or deviant results into account (the goal of the survey may for example need to be revised, if the contamination level for an object differs much from what was expected).

4.3.4 Recommended implementation of survey measurements

In order to carry out survey measurements as efficiently as possible, it is recommended that the measurement efforts and execution are adapted to the risk categorisation made in conjunction with the initial assessment. A proposal for implementation for the different risk categories is described below. The description assumes that the object will be dismantled and demolished and that it will not be used (or be in operation) after the survey measurements.

The description assumes that material samples for determination of penetration depth and nuclide vectors are only taken in areas with contamination above the clearance limit. If there are no such areas, the survey must be supplemented with material samples from areas with lower risk categories.

Extremely small risk of contamination

Objects in this category do not need to be cleared and no survey of the presence of radioactivity is necessary. However, some verification is needed of the categorisation *extremely small risk of contamination*. The following steps are proposed:

- Measure the activity at points where the probability of finding contamination is the highest.
- Delimitate/seal off the area and manage it so that it will not be contaminated.
- If contamination is detected, the object or part of the object shall be recategorised under small risk (or higher). The same applies for dismantled material.

Small risk of contamination

For objects categorised as only *small risk of contamination*, survey measurements are not really needed, since the presence of contamination is improbable. A small amount of targeted measurements may, however, need to be carried out to justify less extensive clearance measurement efforts (compared with objects in the category *risk of contamination*) and to verify that there are no points with elevated contamination. The following steps are proposed:

- If possible, dismantle all process equipment and move all equipment that can be dispensed with and clear it as material or classify it as radioactive waste.
- Register from where the equipment has been dismantled or moved. If contamination is detected on materials, it should be possible to trace where in the room the contamination may occur.

- Conduct a few gamma spectroscopy measurements for larger surfaces (uncollimated detector) to determine the average activity and the relation between gamma-emitting nuclides (if there is contamination).
- Conduct some measurements with scintillation equipment and take smear samples where the probability of finding contamination is highest.
- Alternatively, a gamma camera can be used for localising (or rejecting the presence of) contaminated areas.
- If contamination below the clearance level is detected or if the gamma spectroscopy measurements suggest that there are contaminated areas, the object or part of the object shall be surveyed further according to the category risk of contamination. Here, a subjective assessment of which activity levels can be tolerated in the category small risk of contamination is required.
- If contamination above the clearance level is detected, the object or part of the object shall be recategorised under contamination above the clearance limit.

Risk of contamination

For objects in this category, survey measurements are of great importance in order to minimise the risk that contamination above the clearance level is encountered in connection with clearance measurements. However, it is possible that parts of the object are clean, so it is desirable that the results of the survey measurements as far as possible can be reused in conjunction with analysis of clearance measurements. The following steps are proposed:

- Carry out the first to the fourth point in the list for small risk of contamination above (if they have not been carried out earlier). The need for traceability when it comes to dismantled/moved material is greater here, as the risk of contamination is higher.
- Conduct some measurements with scintillation equipment and take smear samples to cover the entire surface of the object. In order to analyse the spatial variation of the contamination, the distance between measurement points must not be too large (see Desnoyers and Dubot 2012). If previous measurements have not indicated any contamination, it might be appropriate to distribute measurement points independently and equally (see Section 8.5). In this way, the measurements can be combined with clearance measurements, if contamination above the clearance level is not encountered.
- Conduct scanning measurements with scintillation equipment to locate contamination (or use a gamma camera). The purpose of these measurements is to identify small areas with increased activity that could otherwise be missed in the sampling measurements.
- Conduct an analysis of the distribution of activity for the object (for example by geostatistical methods).
- Conduct a larger number of measurements with scintillation equipment where the analysis shows information gaps.
- If contamination above the clearance level is identified, the object or part of the object shall be recategorised under contamination above the clearance limit. If contamination is not detected, the object can be recategorised under small risk of contamination. If only contamination below the clearance limit is detected, the object can undergo clearance measurement according to the category *risk of contamination*.

Contamination above the clearance limit

In small areas, highly contaminated areas or areas where it is known beforehand that the contamination is evenly distributed, it is not meaningful nor appropriate from an ALARA perspective to conduct surveys. These areas should first be decontaminated and thereafter categorised as *risk of contamination* for clearance measurement. The contamination should, however, be sampled for nuclide-specific analysis.

In large areas where the contamination level varies, there is reason to limit decontamination efforts in order to cover only the contaminated parts of the object. If it can be justified from an ALARA perspective, the object can be surveyed first in order to identify contaminated areas. The following steps are proposed:

- Carry out the first and second point in the list for small risk of contamination above (if they have not been carried out earlier).
- Carry out the second to the fourth point in the list for risk of contamination (if they have not been carried out earlier).
- Conduct a larger number of measurements with scintillation equipment around contaminated areas.
- Conduct a new analysis of the distribution of activity for the object in order to delimit areas that must be decontaminated.
- Sample the contamination for nuclide-specific analysis.
- Take material samples in contaminated areas to analyse the penetration in the material (also take samples in fractures, interfaces, outlets etc.). This also applies to penetration in soil.
- Revise the risk categorisation after the comprehensive assessment of survey measurements (some parts of the object may perhaps be delineated and categorised as a lower risk category).

4.3.5 Documentation and management

The results of the survey measurements should be presented in a survey report. In the report, the conclusions drawn in the history report should be revised (see Section 4.2.5). The report should include

- a revised division into subareas,
- a revised risk category for each subarea and its justification,
- measurement results, including the distribution of activity over the surface of the object,
- revised measurement methods,
- revised proposals for decontamination measures,
- an updated nuclide vector based on measurement data.

The project plan and cost estimate should also be revised with respect to the results of the survey measurements (see Chapter 12).

Surveyed areas should be marked so that it is clear that survey measurements have been performed. Objects in the category *extremely small risk of contamination* or *small risk of contamination* should, if possible, be sealed off so that new contamination is prevented.

5 Decontamination

This chapter describes, in general terms, decontamination prior to clearance measurement of buildings, rooms and land. Decontamination for an entire decommissioning project is in other words not described.

Decontamination is carried out in part to permit clearance of objects with contamination above the clearance limit and in part to wherever possible remove loose contamination in accordance with SSM's general advice to 7 § SSMFS 2011:2 (SSM 2011). When removing contamination, the aim should be a remaining contamination equivalent to a tenth of the regulatory clearance levels.

Decontamination is normally carried out after completed survey and risk categorisation, i.e. when there is an idea of the extent and spread of the contamination. In some cases, however, it may be necessary to carry out decontamination before the survey measurements are conducted, for example for highly contaminated areas where survey measurement before decontamination would lead to unacceptable doses to the personnel.

Decontamination may also be needed after clearance measurement has been carried out, in cases where the object is not clean enough. Such a late discovery should be avoided, if possible, since delayed decontamination may affect surrounding objects (by spread of radioactivity) that are potentially already clearance measured. If there is extensive need for decontamination after clearance measurement of an object, the quality of the work in previous stages in the clearance process (see Section 2.2) should be questioned.

The extent of the decontamination efforts should be adapted to the object's risk categorisation:

- For objects in the category small risk of contamination, no decontamination is required for radiological reasons.
- For objects in the category risk of contamination, decontamination may be required prior to clearance measurement if the results of the survey indicate the presence of loose contamination or contamination above clearance levels. If it is known beforehand that loose contamination below clearance levels occurs, it might be appropriate to remove it even before the survey measurements to avoid spread of contamination.
- For objects in the category contamination above the clearance limit, decontamination may be required even before the survey measurements are performed.

5.1 Choice of decontamination methods

Already after the initial assessment and risk categorisation (see Section 4.2), it should be possible to identify suitable decontamination methods with regard to the expected presence of radionuclides and material and surface properties.

When selecting decontamination methods, the following should also be taken into consideration:

- Techniques to prevent spread of contamination.
- Minimising the amount of waste.
- Waste management and potential for final disposal of the waste.
- Methods for verification of decontamination results.

Cross contamination during or after the radiological survey must be avoided as far as possible, since it not only jeopardises the risk categorisation, but also leads to uncertainty and increased costs as additional decontamination and recategorisation may be required.

The risk of cross contamination can be managed by sealing the rooms that can be assumed to be free of contamination and by isolating areas during decontamination, for example by temporary barriers, and ventilation systems that prevent the dispersion of contaminated dust.

United States Environmental Protection Agancy has compiled a detailed description of decontamination methods for contaminated surfaces and contaminated media and land (EPA 2006b, 2007). The Clearance Manual (SKB 2011) also proposes a number of decontamination methods for building and rooms surfaces.

These guidelines are intended as an aid in decision-making, but if there is no proven experience, it might be appropriate to gather information to support the choice of measures and implement this through a small-scale demonstration. This often entails laboratory-based tests that can provide important information on how the proposed technology will perform during specific real conditions.

5.2 Implementation

How effective the methodology for decontamination is depends on project-specific conditions. An extensive decontamination effort with the aim of removing all potential contamination is often time efficient (in terms of calendar), as the risk of ending up in an iterative process with decontamination and supplementary surveys in several steps is reduced. The disadvantages are that the amount of waste increases and that the work effort for decontamination will probably be considerably larger. If there are advantages with minimum waste generation, a methodology should be selected where known contamination is removed after which the object is surveyed again (or undergoes clearance measurement directly).

In order to achieve efficient execution of the decontamination required, the following work method is recommended:

- Specify and delimit the activities:
  - Decide what should be decontaminated.
  - Choose methods and criteria for each activity.
- Set clear goals:
  - What criteria should be fulfilled for decontamination to be considered sufficient.
- Begin primarily at the top of buildings and decontaminate downward, from within and out, and secondarily with the most contaminated surfaces and continue to cleaner areas.
- Work building by building and room by room.
- Ensure that the waste generated is managed continuously.
- Document the activities continuously:
  - What has been done and with which method?
  - What has been achieved?
  - Document the origin and properties of the waste.

Experience from completed decommissioning projects shows that it is often more efficient to remove more material at decontamination. A cleaner object can be cleared faster, and the risk of needing to carry out supplementary decontamination and new clearance measurements decreases. It is also compatible with the general advice to SSMFS 2011:2 (SSM 2011), that a tenth of the regulatory clearance levels should be the goal when removing loose contamination.

Removal of extra material at decontamination in order to achieve clearance for the removed material is, however, neither good practice nor allowed (SSM 2011). In practice this entails that it can be necessary to justify why for example concrete is shaved off a wall evenly over the surface down to the rebar in a room, instead of shaving the wall one piece at a time with subsequent measurements. Regardless of if the removal is done evenly over the surface or one piece at a time, the removed material is to be regarded as waste and must be treated as such.

5.2.1 Verification of decontamination results

It is desirable that the decontamination methodology also includes a methodology for verifying that decontamination has been sufficient for the object to undergo clearance measurement. Verification is preferably carried out with the same measurement methods used during survey measurements. However, the extent should be more limited with random measurement of activity in the measurement points where contamination was encountered during survey measurements.

In order to exclude that contamination may have spread to other parts of the object, a few new measurements can also be made for measurement points close to the decontaminated areas, where contamination has not previously been detected. However, it is not meaningful to carry out such measurements before the decontamination results are verified.

6 Determination of nuclide vectors

A large number of the nuclides that can be expected to occur in the contamination at nuclear facilities are to be regarded as difficult-to-measure and cannot be detected at measurements *in situ*, regardless of whether the measurements are made with nuclide-specific methods or not. Nuclide vectors, which indicate correlation factors for constituent nuclides (level of activity relative to some measurable key nuclides, or relative to the total activity), are therefore absolutely necessary in order to perform clearance based on nuclide-specific clearance levels.

Recommendations for how nuclide vectors should be determined are described below (see also examples in the Clearance Manual (SKB 2011), Appendix 3).

6.1 Estimated presence of radionuclides

As a basis for the design of the final repositories for decommissioning waste, nuclide-specific inventories of radioactivity have been estimated for all Swedish nuclear power plants. The studies were based on operating histories to date and forecasts for future operation of the facilities that have not yet been taken out of service. The methodology is described by Lundgren (2012).

The nuclides included in these studies are based on a list agreed on with SKB, which is coordinated with the report that is made for operational waste to SFR. The list includes a total of 48 nuclides, all with half-lives greater than a year, and is presented in Table 6-1. This list of nuclides can be used as a starting point for developing a nuclide vector for clearance during dismantling and demolition of facilities that correspond to the Swedish nuclear power plants with regard to the presence of radioactivity. This requires that clearance occurs after a period of decay. For clearance shortly after shutdown, more short-lived nuclides should also be taken into account, for example Co-58 in PWR plants[2]. In these cases, the facility's safety analysis report for operation should provide information on occurring nuclides.

The studies can also be a basis for calculating the average surface activity for neutron-irradiated and contaminated concrete. Although there are variations between the reactors (above all between PWRs and BWRs), by comparing these average surface activities with the clearance levels for each nuclide, it can be concluded that:

- Co-60, Cs-137 and Cs-134 are dominant for clearance of contaminated surfaces and materials,
- Eu-152 and Co-60 are dominant for clearance of neutron-irradiated concrete,
- Ag-108m, Eu-154 and transuranics may need to be considered.

For clearance after a long decay time, it is, however, possible that more long-lived nuclides will be bounding when the level of radioactivity for Co-60 has decreased.

The nuclides that are in the list, but have no stipulated clearance levels, occur in such limited extent (in relation to other nuclides) that they, for all reasonable values for clearance levels, will not affect the potential for clearance.

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[2] Due to loosening of corrosion from Inconel surfaces in the steam generators, significant quantities of Ni are released to the reactor water, which is then activated in the core and forms Co-58.

Table 6-1 . Nuclides occurring in the Swedish nuclear power plants of relevance for clearance. The nuclides stem from fuel (Fuel) and/or activation of engineering materials (Ind).

Nuclide	t½ /yr	Principal origin	Nuclide	t½ /yr	Principal origin
H-3	12.3	Fuel, Ind(B, Li)	Cs-135	2.30E+06	Fuel
Be-10[1]	1.60E+06	Fuel, Ind(Be, B)	Cs-137	30	Fuel
C-14	5700	Fuel, Ind(N)	Ba-133[1]	10.5	Fuel, Ind(Ba)
Cl-36	3.01E+05	Ind(Cl)	Pm-147	2.62	Fuel
Ca-41[1]	1.03E+05	Ind(Ca)	Sm-151	90	Fuel, Ind(Sm)
Fe-55	2.73	Ind(Fe)	Eu-152	13.5	Fuel, Ind(Eu)
Co-60	5.27	Ind(Co)	Eu-154	8.59	Fuel, Ind(Eu)
Ni-59	7.60E+04	Ind(Ni)	Eu-155	4.75	Fuel
Ni-63	101	Ind(Ni)	Ho-166m[1]	1200	Fuel, Ind(Ho)
Se-79[1]	1.10E+06	Fuel, Ind(Se, Br)	U-232	69.8	Fuel
Sr-90	28.8	Fuel	U-236	2.37E+07	Fuel
Zr-93	1.53E+06	Ind(Zr)	Np-237	2.14E+06	Fuel
Nb-93m	16.1	Ind(Nb)	Pu-238	87.7	Fuel
Nb-94	2.00E+04	Ind(Nb)	Pu-239	2.41E+04	Fuel
Mo-93	4000	Ind(Mo)	Pu-240	6563	Fuel
Tc-99	2.14E+05	Fuel, Ind(Mo)	Pu-241	14.3	Fuel
Ru-106	1.02	Fuel	Pu-242	3.74E+05	Fuel
Ag-108m	418	Fuel, Ind(Ag)	Am-241	433	Fuel
Pd-107[1]	6.50E+06	Fuel	Am-242m	141	Fuel
Cd-113m[1]	14.1	Fuel, Ind(Cd)	Am-243	7365	Fuel
Sn-126[1]	2.30E+05	Fuel	Cm-243	30	Fuel
Sb-125	2.76	Fuel, Ind(Sn)	Cm-244	18	Fuel
I-129	1.61E+07	Fuel	Cm-245	8500	Fuel
Cs-134	2.07	Fuel, Ind(Cs)	Cm-246	4730	Fuel

[1] The nuclide has no stipulated clearance level.

6.1.1 Other facilities

When it comes to other nuclear facilities, nuclide vectors need to be determined in a similar manner as for BWR and PWR facilities.

For the research reactor R2 in Studsvik, it should be particularly noted that significant activation of aluminium has taken place, and that the pool walls consist of an aluminium lining and iron ore concrete with another composition than for example concrete in the biological shield for Swedish BWRs and PWRs. Furthermore, it should be taken into account that tanks with heavy water, and thereby production of tritium, have been a part of the construction, which in the event of leakage may have given rise to contamination of concrete. Furthermore, the irradiation activities that have occurred must be considered, which may have resulted in contamination with nuclides specific for the facility.

For the closed heavy water reactor Ågesta, the concentration of tritium in the reactor water must be considered, since tritium from the reactor water may have spread and contaminated engineering materials in the facility (e.g. concrete that have been exposed to reactor water leakage).

Calculated nuclide vectors for the Clab facility, show large similarity with those in BWRs and PWRs. A distinction is, however, relatively high concentrations of Cs-137 in relation to Co-60 in the storage pools. Concrete in Clab, which has been contaminated due to leakage, can thereby be expected to have a higher content of Cs-137 (in relation to Co-60) compared with contaminated concrete from BWR and PWR plants.

The facility in Ranstad has contamination in the form of material containing uranium, including decay chains, and thus deviates from the other facilities.

6.2 Determination of correlation factors

Most of the long-lived radionuclides in radioactive waste are difficult to quantify with ordinary gamma measurements. In most cases, time-consuming chemical separation methods are required before the activity can be determined. Nuclide vectors can be used for estimating the radioactive content for these difficult-to-analyse radionuclides, where correlation factors between difficult-to-analyse nuclides and reference nuclides are used. The prerequisite is that there is a reasonable correlation between the difficult-to-measure nuclide and the reference nuclide.

For determination of the radioactive content for building parts, as a basis for decisions on clearance, the following methodology is suggested:

- The basic theoretical nuclide vectors should be updated before dismantling and demolition with respect to operating history up until shutdown of the facility, and the decay time up until the survey.
- Different building parts should be grouped into areas where reasonably equal vectors can be assumed. The aim should be to restrict the number of vectors, so as not to unnecessarily complicate the determination of activity.
- Validation measurements for the vectors should be carried out as follows:
    - Gamma spectrometry measurements should be made for selected surfaces, and for samples from contaminated areas. The number of measurements should be chosen so that reasonable statistics are obtained.
    - In a few cases, samples for laboratory measurement are taken for determination of certain nuclides that are difficult to measure from the aspect of final disposal. Examples of nuclides that should be determined in relation to the reference nuclides Co-60 and Cs-137 are Ni-63, Mo-93 and alpha-emitting transuranics.
- The theoretical vectors are adjusted based on validation measurements.
- The correlation between count rate measurement with a scintillation detector and the activity for each nuclide vector is determined by calibration against calibration specimens, or, when needed, calibration through count rate measurement in the positions that have undergone gamma measurement.
- Through the determined correlations between net count rate (corrected for background radiation) and activity according to each nuclide vector, limits for clearance are determined according to the scintillation measurements.

6.3 Handling of uncertainties

The nuclides that are expected to affect clearance the most are also those that are easiest to measure and, therefore, quite large uncertainties can be tolerated for the more difficult-to-measure nuclides. For certain nuclides, however, it will be difficult to determine the activity levels in other than a very small number of samples. It will then be difficult to say anything about the activity level or the uncertainty for these nuclides. In such cases, calculated values can be used (adapted to the measured activity of detectable nuclides). It is then recommended to choose a very conservative value and disregard the uncertainty, or assign a generous uncertainty.

The quantitative uncertainty has, in the studies mentioned in Section 6.1, been set to a factor of 3 for the calculated total activity in biological shields and at least one order of magnitude for calculated activity on contaminated building surfaces. The uncertainty in the nuclide vector can be incorporated in the statistical analysis of the results from clearance measurements, according to Section 8.3.4.

In order to minimise the number of material samples and costly laboratory analyses, the number of nuclide vectors should be limited. However, if the nuclide vector varies greatly between different parts of an object, we should consider dividing the object into different parts and determining a nuclide vector for each part. This is particularly true if the variation indicates that the contamination has different origins. Alternatively, clearance measurements with nuclide-specific gamma spectroscopy can be relied on to a greater extent, in order to consider variations in the relationship between gamma-emitting nuclides.

7 Clearance measurement

Clearance measurement refers to the check for radioactivity that serves as a basis for a decision on clearance. It is described in the control programme for rooms, buildings, land and materials above 100 tonnes/yr, that shall be submitted to SSM before clearance measurement begins. As for the radiological survey, it is important to carefully plan the clearance measurements and that measurement data can be managed in a systematic and quality assured manner.

Clearance measurements will serve as a basis for the statistical analyses that should show that the activity level for an object does not exceed the regulatory clearance limit. Furthermore, for clearance it must also be shown that loose contamination has been removed to a sufficient extent and that it is not likely that there are points with locally elevated activity that may have been missed during clearance measurement. For the two latter analyses, however, there are no regulatory requirements to relate to.

According to 7 § SSMFS 2011:2 (SSM 2011), the methods and extent of the check for radioactivity prior to clearance should be adapted to the estimated presence of radioactive contamination. Therefore, it is recommended that the risk categorisation is also used for adapting the extent of clearance measurements. This is also in line with the IAEA's recommendations (IAEA 2012).

Furthermore (in accordance with 7 § SSMFS 2011:2), clearance measurement should be adapted to the properties of the object. For clearance of land, clearance measurement should include a measurement of radioactivity as a function of depth, while clearance measurement for buildings and rooms is preferably conducted with respect to surface activity. For concrete and other porous materials, however, penetration of radioactivity into the materials must also be considered. The IAEA's recommendations (IAEA 2012), as well as other guidance documents (for example MARSSIM (NRC 2000), NICoP, SKB 2011), provide more examples of how clearance measurements should be adapted to different materials.

7.1 Planning of clearance measurements

Clearance measurements will usually be considerably more extensive than the survey measurements described in Chapter 4. The reason for this is that clearance measurements should show, with high statistical certainty, that an object can be cleared, while survey measurements mainly aim to provide a basis for decisions on further management of the object. For this reason, it is also important to carefully plan the execution of clearance measurements in detail. In addition to choosing measurement methodology and sampling strategy, it should be decided in advance how measurement data will be stored and processed and what analysis methodology will be applied. For this purpose, it should be possible to use the same systems as in the radiological survey (see Section 4.3.3).

It is also important to prepare instructions for how clearance measurements should be carried out in practice, how quality assurance should be implemented and what competence is required to carry out the measurements and analyse the results, and who is authorised to make decisions during the course of the process (see Chapter 10).

The planning of clearance measurements should be documented in the control programme (whose content is defined in Chapter 9). In conjunction with this planning, it is also appropriate to update the project plan and cost calculation (see Chapter 12) for clearance, as the extent and resource requirements of the clearance measurements are concretised.

7.1.1 Choice of measurement methods

The results from the radiological survey should give sufficient information for selecting the best suited methods for clearance measurement. The following is a description of the properties of the measurement object and the measurement method that should be taken into account when selecting a measurement method for clearance measurement.

Measurement object

The necessary extent of measurements vary depending on whether it is a building or a room or if it is land, and depending on the assessed risk category. It is also important to consider the previous history and usage of the facility. The choice of measurement methods is affected by whether a thick layer of contamination or thin surface contamination has previously occurred, and an assessment of the contamination's penetration into the material. The contamination's distribution thus needs to be determined (see Section 7.2.2).

Different materials and geometries may need to be taken into account in scintillation measurements. The equipment manufacturer's documentation and experts should be consulted in order not to risk performing clearance measurements with questionable quality or little value.

The extent of measurements and sampling for clearance of land differs from clearance of buildings or rooms, since radioactivity may have been transported and spread in the ground. The three-dimensional distribution of activity thus needs to be considered when selecting a measurement method for land. This, together with the need for consultation with stakeholders, means that clearance of land requires another timetable than clearance of buildings or rooms.

The background radiation of the object to be measured must also be taken into account when selecting a measurement method. It may, for example, require nuclide-specific measurements to distinguish background radiation from contamination. The possibility of correcting for background radiation by pairwise measurements with a shielded and unshielded detector (for scintillation equipment) needs to be studied. This type of background correction simplifies the statistical analysis, but if it is not possible a separate determination of the background level for the object must be made, or the clearance measurements must be conducted without background correction.

Nuclide composition

The Clearance Manual (SKB 2011) describes the possibility of clearance based on scintillation detection and nuclide vectors. Suitable sources for identifying nuclide vectors may be the SAR, nuclide-specific *in situ* and/or *ex situ* measurements, relevant analyses for other materials, or other relevant facilities (see Chapter 6 in this report). It is not possible to perform clearance without nuclide-specific information relevant for the facility, and this information, in reality, often comes from several sources. With good documentation of the facility, the need for nuclide-specific *in situ* measurements is reduced.

Nuclide composition also affects the choice of measurement method in the sense that radioactivity from occurring nuclides must be possible to detect with such accuracy that radioactivity below the clearance level can be detected with certainty. If the nuclide vectors are known and stable for the facility, the possibility of basing the clearance measurements on a measurement of the total activity rather than nuclide-specific measurements increases.

The efficiency factor of the measuring probe (total activity per count rate) must then be determined by measuring the count rate for samples/measurement points where the nuclide composition is known from for example gamma spectroscopy measurements. The analysis may also need to be supplemented with a calculation of the expected count rate, based on the equipment's specified sensitivity to certain radiation and a given nuclide composition.

With knowledge of the ratio between count rate and total activity, a measured count rate can be converted to a nuclide-specific surface activity, by means of a nuclide vector that describes occurring nuclides' activity in proportion to the total activity. Even the activity of nuclides that the detector is not sensitive to can then be calculated.

In case of uncertainty, it should be possible, with a few gamma-spectroscopy measurements, to show whether a certain nuclide vector is valid for a certain object. This also gives the possibility to determine the ratio between some gamma-emitting key nuclides and based on this calculate an adapted nuclide vector for the specific object.

Measurement uncertainty

Since the measurement method's uncertainty must not be greater than to permit, with certainty, detection of radioactivity close to the limit for clearance, measurement uncertainty must also be considered when selecting a measurement method for clearance measurement. This overall requirement in turn imposes requirements on the measurement system, on individual measured values and on the sampling strategy. Simply expressed, the following requirements are imposed:

- Minimum detectable activity (MDA) must correspond to a presence of radioactivity well below the requirement for clearance. MDA can be calculated according to instructions in SS-ISO 11929:2010 (SIS 2010). MDA should be calculated for the measurement time that is practically applicable with respect to the extent of the measurement programme.
- Individual measured values must not exceed the requirement for clearance. An operational limit for the measured count rate should be defined, in order to immediately detect areas that must be decontaminated (see Section 8.6).
- Measurement points for clearance measurement shall be independent and equally distributed (SS-ISO 11932 (SIS 1997) recommends a stratified random selection).
- The number of necessary measurements for a building or a room can be determined according to the instructions in SS-ISO 11932 (SIS 1997) (the same methodology can be used for land). The possibility of reusing measurement results from the radiological survey should also be considered.
- The acceptable risk level for occurrence of anomalies (hot spots) also imposes requirements on the number of measurements (see Section 8.7).

For nuclide-specific measurement, some (occurring and measurable) nuclides will presumably not be detected for each measurement area, since the level of activity for certain nuclides could be well below the MDA. It is then necessary to either assign a highest probable activity value to these nuclides (for example MDA/2), to calculate the activity by means of a nuclide vector or to justify when and why the presence of these nuclides can be excluded.

7.2 Implementation of checks for radioactivity

Existing measurement methods for clearance measurement of buildings, rooms and land can be divided into methods for measurement of total activity, and methods for nuclide-specific measurement. Measurement methods can also be divided into *in situ* and *ex situ* and the type of nuclide-specific measurement, see further Table 6-1 in the Clearance Manual.

For buildings, rooms and land, it is preferable to perform most of the measurements (both total activity and count rate*)* *in situ* with a hand-held instrument. In order to be able to correlate between the different measurement types, supplementary nuclide-specific measurements can be conducted with *in situ* gamma spectroscopy (for example ISOCS or ISOTOPIC). This can be carried out by pairwise measurements that ensure, by means of shielding or collimation, that the detectors for each measurement method records activity from the same area. This combination provides good prospects for cost-effective clearance measurement.

In order to check loose contamination, smear tests are used, whose results and accuracy is affected by several factors, see further the Clearance Manual Section 6.3.1. Results from smear tests can serve as a complement to other clearance measurements.

Material samples are normally analysed *ex situ* for total activity or nuclide-specific activity. Regarding the theory for nuclide-specific measurement, see Gilmore (2008) and the Clearance Manual (SKB 2011).

The implementation of clearance measurements (for potentially surface-contaminated objects) should be adapted to the object's risk categorisation according to the following:

- For objects with small risk of contamination and no previous contamination, the following applies:
  - Surface activity is measured by sampling, and each measurement value must have sufficient quality (see Section 7.1.1).

- For objects with small risk of contamination, but with previously observed contamination below the clearance limit, the following applies:
  - Surface activity is measured by sampling, and each measurement value must have sufficient quality (see Section 7.1.1).
  - Random smear samples should be taken to ensure that loose contamination does not occur, unless smear samples from survey measurements can be considered sufficient.
  - 100 % of the surface is measured with lower requirements on measurement data. In practice, scanning (lower integration time) with a scintillation detector is used. The scanning measurement must, however, be carried out in a systematic and controlled manner so that MDA can be estimated.
- For objects with risk of contamination, the following applies:
  - Surface activity is measured for 100 % (an integrated measurement over each m^2) of the surface, and each measurement value must have sufficient quality (see Section 7.1.1).
  - Smear samples should be taken to ensure that loose contamination does not occur, unless smear samples from verification of decontamination can be considered sufficient.

For clearance of land, clearance measurements should be adapted in the corresponding way. At lower risk, sampling measurements can be considered sufficient, possibly supplemented by gamma spectroscopy measurements on the ground surface, in order to assess surface contamination over a larger area. At higher risk of contamination (for example adjacent to areas with known contamination above the clearance level), it may be necessary to excavate and measure the excavated material to obtain an extent of measurements corresponding to a comprehensive measurement.

During clearance measurement, the licensee should conduct random independent measurements to ensure that the clearance measurements are of sufficient quality (see Section 10.3.3). It is also appropriate to analyse the results continuously in order to be able to decide on extended clearance measurements or decontamination measures.

If an area turns out to require decontamination, the clearance measurements should be interrupted until the area is decontaminated. After decontamination, the clearance measurements can be resumed. The decontaminated area should then be inspected to 100 % of the surface according to the bullet list above. Furthermore, already performed measurements should be repeated in areas adjacent to the decontaminated area to ensure that they have not been contaminated again.

When clearance measurements are completed, the area should be closed off, sealed and managed so as not to risk that the area is contaminated again.

7.2.1 Checks for loose contamination

In the general advice to 7 § SSMFS 2011:2 (SSM 2011), it is stated that loose contamination should be removed if it can be done with simple methods. Therefore, the check for radioactivity should be supplemented with an analysis of smear samples from the surface of the object. The general advice states that a tenth of the stipulated clearance levels should be the aim of remedial action.

It should be possible to use data from surveys and decontamination to show that the recommendations above have been fulfilled, but for objects in the category *risk of contamination,* additional smear tests may be necessary to show that all loose contamination has been managed.

7.2.2 Checks of the distribution of activity and anomalies

In random checks for radioactivity, there is always a risk that there is one or more points with activity above clearance levels that have not been detected and that deviate from the distribution of activity for the rest of the object. Clearance measurements should therefore be supplemented with an analysis of the risk that one or more such anomalies occur.

Section 8.7 presents a statistical method for this, but this analysis requires a decision on what is a reasonable risk level. In order to justify such a decision for a certain object, a supplementary check of the object's distribution of activity can be conducted. This can be done by for example scanning count rate measurements over the entire surface of the object/subarea, or by means of a gamma camera.

These techniques are generally not sensitive enough to be used for clearance, but if no activity is detected in these checks, the MDA for the chosen measurement method can be assigned the highest possible value for a hypothetical anomaly. This peak value can then be used to argue that a certain risk level for the occurrence of anomalies is acceptable.

For scanning count rate measurements over the whole surface, the following should be considered:

- Several probes can be used at the same time for increased efficiency.
- The probes can be mounted on a carriage (see Appendix B) and rolled with an even speed across a surface in a predefined pattern.
- Scanning measurements give a higher MDA compared with measurements with a stationary probe. Methods for determining MDA in scanning measurements are described in, for example, MARSSIM (NRC 2000) Chapter 5.

Count rate measurements can also be supplemented by gamma spectroscopy measurements over larger surfaces of the object. The measurements provide a gamma spectrum, corresponding to the total activity for a large surface from which the average activity can be calculated. If this mean value does not deviate from the mean value calculated from count rate measurements, it can be used as support that the count rate measurements cover enough of the object's surface. The uncertainty in gamma measurements is, however, crucial for how large anomalies may have been missed.

Penetration of activity into porous materials must also be taken into account in connection with clearance measurements. The extent of penetration of activity into various materials should have been studied in conjunction with survey and clearance measurement. This information should be possible to reuse in connection with clearance measurements. In other cases, supplementary sampling and analyses must be carried out in connection with clearance measurement. Gamma spectroscopy measurements may be advantageous here, as gamma radiation from shallowly penetrated activity and activity in fractures can be detected and distinguished from background radiation. For clearance according to surface-specific clearance levels, all activity should be attributed to the surface. Measured surface activity should thus be adjusted to include underlying activity.

For clearance of land, it is also necessary to check the extent to which radionuclides may have been transported from the original site of contamination. Since the site-specific conditions that affect the transport of radionuclides must be studied for derivation of clearance levels for land (see Chapter 11), some of the information that emerges there should be possible to use to identify any additional clearance measurements that need to be conducted to cover the three-dimensional distribution of radionuclides in the ground.

7.2.3 Measurement site

In order to conduct clearance measurements of material during decommissioning, there should be a specific measurement site (with low background radiation but close to the facility) for clearance measurement of dismantled components. The measurement site should be able to conduct clearance measurements for a large flow of materials with nuclide-specific gamma spectroscopy.

At the measurement site, material samples may also be handled and calibration between different measurement techniques performed. Such a measurement site will therefore also be needed for clearance of rooms, buildings and land, even if the majority of clearance measurements are then carried out *in situ*.

7.3 Documentation

After completed clearance measurement, the results should be documented in a clearance report, which will also serve as a basis for the application for clearance of rooms, buildings and land.

The report shall describe how the clearance measurements have been conducted in relation to the description in the control programme. The report should also present the results of the statistical analysis of measured values. Since the report will be used to make decisions regarding clearance (or continued use in the licensee's activities), it is important that the report is quality assured (see Section 10.3.4).

8 Statistical evaluation of clearance measurements

For clearance of buildings and rooms as well as land, clearance measurements will be performed by random sampling rather than as a complete scan of all surfaces. Extensive statistical analysis will therefore be required to show that the requirements for clearance are met in the application for clearance. This chapter describes a proposal for a statistical methodology for analysis of data from clearance measurements (a hypothetical example is given in Appendix E).

The uncertainty in the assessment of the presence of radioactivity in a larger object such as a building is dependent on the uncertainty in a number of different parameters:

- Spatial variation of contamination.
- Uncertainty in the measured net count rate.
- Uncertainty in detector efficiency.
- Uncertainty in the nuclide vector.

Calculating the combined uncertainty from these different parameters may appear difficult, but the alternative is to rely on very conservative assumptions. The latter will lead to unnecessary limitations of what objects can be cleared and as a consequence, increased quantities of waste.

Considering the great efforts that will be spent on measurement in conjunction with survey and clearance measurement, it is warranted to conduct a thorough statistical analysis of the uncertainty regarding the presence of radioactivity.

This section describes the statistical methodology that should be the basis for assessment of uncertainty in the results from clearance measurements. The methodology is described on the basis of clearance measurements performed by count rate measurement of the total activity. However, it is entirely possible to transfer this methodology to clearance measurements with nuclide-specific *in situ* measurements.

8.1 Interpretation of compliance

The requirement for clearance according to nuclide-specific levels is defined by the sum of fractions of the clearance levels for the radionuclides present (SSMFS 2011:2), according to the following equation (in continuation called the sum criterion):

$$inteckning = \sum_{i}^{N} \frac{C_i}{C_{FNi}} \leq 1$$

where C_i and C_{FNi} are the activity and clearance level, respectively, for nuclide *i* per unit mass or area, and *N* is the number of nuclides occurring.

For clearance of materials, the activity concentrations may be calculated as a mean value over a maximum of 1000 kilograms. No maximum permissible area for mean value calculation is specified for the application of clearance levels per unit area (for buildings and rooms), but according to the regulations, the clearance levels should be applied to each square metre of the surface. The interpretation of this is that the sum criterion may not be exceeded for surface activity calculated as a mean value over 1 m^2.

However, it can never be proven with 100 % certainty that the activity in an object will not exceed the clearance levels or that the assessment of total activity does not exceed the sum criterion. It is possible, though, to calculate the probability of exceeding a specified limit. The following are some statistical measures that can be used to show that clearance requirements are met based on random sampling.

In addition to these calculated results, the clearance measurements must also meet the requirements for individual measured values (Section 8.6) and must be supplemented with an analysis of the risk of occurrence of pointwise contamination with high radioactivity (*hot spots*), hereinafter referred to as *anomalies* (see Section 8.7).

8.1.1 UCL95

UCL95 indicates the level which the expectation value for a population will not exceed with a credibility (certainty) of 95 %. UCL stands for *upper credibility limit* and 95 refers to 95 % probability. UCL95 is a suitable measure to show that the sum criterion has not been exceeded with respect to the average activity. If UCL95 for the sum is less than 1, it is likely (at more than 95 %) that the sum criterion concerning average activity is met. The measure UCL95 is above all important when the *quantity* of radioactivity needs to be determined, for example for derivation of clearance levels according to Chapter 11.

8.1.2 P95

P95 indicates a limit for a new (hypothetical) observation (i.e. an upper limit in a prediction range). P95 indicates a limit that with 95 % credibility will not be exceeded for instance in a new measurement. P95 is therefore a suitable measure for the sum criterion not being exceeded in any square metre, and can thus be used as a basis for the application for/decision on clearance. If $P95 < 1$, it is likely (at more than 95 %) that a new measurement (given that a measurement relates to activity for a m^2 or a tonne, depending on which clearance levels are applied) would not demonstrate activity above the clearance limit.

8.2 Mean value calculation for surface-specific activity

For measurement with single readings with scintillation equipment, the mean count rate is measured over the detector surface (~ 0.01 m^2). If the standard deviation of these measurements is determined as s, the standard deviation of a mean value over 100 independent measurements will be a factor of 10 lower ($s/\sqrt{100}$). There is therefore reason to believe that the mean value over 1 m^2 has a considerably lower standard deviation than the standard deviation of the individual measurements. Since measurement of adjacent surfaces in order to calculate the mean value over 1 m^2 (integrated measurement) is presumably not independent, the correct factor is probably lower than 10. If the statistical evaluation is based on the standard deviation of a single reading, the assessment of uncertainty will be conservative. However, it is possible to determine how the standard deviation for single readings could be scaled to correspond to the standard deviation for measurement over 1 m^2, and then to use the scaled standard deviation in the uncertainty analysis.

8.3 Uncertainty analysis

This section describes how different contributions to uncertainty are to be assessed and combined in a final analysis of the total uncertainty in the assessment of whether an object can be cleared.

The sum criterion can be written as:

$$\gamma_D r_N b_R \leq 1 \tag{8-1}$$

where γ_D is the scintillation efficiency (Bq cps^{-1}), r_N is the mean net count rate (cps/m^2 or cps/kg), and b_R ($Bq^{-1}m^2$ or $Bq^{-1}kg$) is the clearance constant, which is defined as:

$$b_R = \sum_i^n \frac{p_i}{C_{FNi}}$$

where p_i is the proportion of activity for nuclide i in the relevant nuclide vector. γ_D, r_N and p_i must all be determined in connection with clearance, and the uncertainty of these determinations must be calculated.

In order to calculate the combined uncertainty in $\gamma_D r_N b_R$, it must be possible to simulate the input parameters separately with respect to their uncertainty distributions.

Equation 8-1 specifies the clearance condition for a mean net count rate. If the condition is instead made for a single measurement of the net count rate ρ_N, the condition is:

$$\gamma_D \rho_N b_R \leq 1$$

8.3.1 Uncertainty distributions

In the statistical analysis of the sum ($\gamma_D r_N b_R$ and $\gamma_D \rho_N b_R$), it is assumed that the uncertainty in input parameters most often can be described with a normal or log-normal distribution.

In order to determine which distribution best fits the observed data, a comparison can be made of quantiles for data (or log-transformed data) and quantiles for a standard normal distribution. If these quantiles are plotted against each other, the result should be points along a straight line if the data are normally distributed (or log-normally distributed). Data (or log-transformed data) for observation number k (sorted in order of magnitude from the lowest to the highest value) for n observations should then be compared to the value of the cumulative standard normal distribution for p_k where

$$p_k = \frac{2k-1}{2n} \tag{8-2}$$

It is also also possible to apply for example *Lilliefors'* (Lilliefors 1967) normal distribution test. However, it is important to understand that the outcome of such a test answers the question of if the null hypothesis (that data are normally distributed) can be rejected. If the null hypothesis cannot be rejected, though, that does not necessarily imply that the data are from a normal distribution.

In some cases, the data does not support the assumption that the normal or log-normal distribution would be a reasonable model for the uncertainty for a given parameter. It is then necessary to rely on nonparametric statistics to describe the uncertainty, or to base the statistical analysis on only the mean value over the parameter (it follows from the central limit theorem that, for large quantities of data, the mean value can be assumed to have a normally distributed uncertainty even if individual observations are not normally distributed).

Normally distributed data

If x is normally distributed, the uncertainty distribution for the expected value of x (μ_x) is given by a t-distribution with ($v = n - 1$) degrees of freedom according to

$$\mu_x = \bar{x} + t \cdot s_x/\sqrt{n} \tag{8-3}$$

where n is the number of measurement points and s_x and x are the estimates of the standard deviation and mean value calculated from measured data. In simulation, t is deducted from a t-distribution with v degrees of freedom and then μ_x is calculated. The uncertainty distribution for a new measurement value x_i is given by

$$x_i = \bar{x} + t \cdot s_x \sqrt{1 + \frac{1}{n}} \tag{8-4}$$

Log-normally distributed data

On the other hand, if x is log-normally distributed, the following applies:

$$\log x = y \sim \mathrm{N}(\mu_y, \sigma_y)$$

By calculating y after having logarithmised measurement data, the mean value and standard deviation can be estimated (y and S_y) and with these μ_x can be simulated as follows (Gelman et al. 2004):

Draw u from a χ^2 distribution $x^2(v)$ and calculate

$$\sigma_y = \sqrt{\frac{v}{u}} \cdot s_y$$

v is once again the number of degrees of freedom (n − 1). Then draw z from a standard normal distribution and calculate

$$\mu_y = \bar{y} + z \cdot \frac{\sigma_y}{\sqrt{n}} \tag{8-5}$$

In the same way as in the normally distributed case, the uncertainty distribution for an individual value y_i can be calculated as

$$y_i = \bar{y} + t \cdot s_y \sqrt{1 + \frac{1}{n}} \tag{8-6}$$

μ_x and σ_x (expected value and standard deviation of the original scale) are obtained from

$$\mu_x = e^{\mu_y + \frac{\sigma_y^2}{2}}$$

$$\sigma_x = \mu_x \sqrt{e^{\sigma_y^2} - 1}$$

and x_i can be calculated from

$$x_i = e^{y_i}$$

Nonparametric methodology

For data that do not follow any known distribution, an upper limit can nevertheless be estimated according to the following:

Let p_k be the probability that the value for a hypothetical observation x is less than or equal to value x_k for observation number k (sorted in numerical order from the lowest to the highest) of n observations. An estimation $\hat{p}_k$ of p_k can be obtained from Equation 8-2.

By assigning a value to p_k (for example 95 %), k can be calculated from Equation 8-2 and the limit corresponding to the probability p_k is given by the value for the observation x_k in data. If p_k gives a value for k that is not an integer, it is possible to calculate a value for x_k through interpolation

$$x_k = x_i + (x_{i+1} - x_i) \cdot (k - i)$$

where i is the integer part of k.

This estimate is associated with an error, however, and an upper limit can be determined from

$$p \leq \hat{p} + z_\alpha \sqrt{\frac{\hat{p}(1 - \hat{p})}{n}}$$

where z_α is the standard normal distribution quantile corresponding to the risk α ($z_\alpha \approx 1.645$ for $\alpha = 0.05$). From this upper limit for p, a new value for k and x_k can be determined. In order to apply this methodology, relatively large quantities of data are needed, since the upper limit for x_k otherwise risks being outside the range of measured data.

8.3.2 Scintillation efficiency

The scintillation efficiency γ_D can be determined by measurement of the count rate for objects where the activity is known. This can be achieved by double measurements of count rate and activity (with some detector system that provides determination of activity with low uncertainty). γ_D is calculated as the expected value μ_x of the quotient of the measured count rate r divided by the activity a.

$$x = \frac{r}{a}$$

$$\gamma_D = \mu_x$$

γ_D can never be less than 0, which is why it can be reasonable to assume that the data are log-normally distributed, but if μ_x is sufficiently far from 0, a normal distribution may also be appropriate. The log-normal model is probably slightly more conservative, though. From quantile plots and a normal distribution test, a suitable distribution can be assigned.

8.3.3 Net count rate

The net count rate is calculated as the difference between the total count rate r_T and the background r_B:

$$r_N = r_T - r_B$$

The net count rate can be determined either by clearance measurements being performed as paired measurements where the count rate in each point is measured with and without contribution from background (for example by shielding the detector). Alternatively, the background count rate is determined in a separate measurement. A third alternative is to conservatively disregard the background and base clearance solely on r_T.

If r_T and r_B are determined in separate tests, it is not appropriate to simulate r_T and r_B separately and to form the simulation of r_N from these, as this would give negative values for r_N in some cases. Although individual determinations of the net count rate can be negative, the expected value cannot be negative. Screening out such negative values is not a solution to the problem, since it would result in a non-representative selection from the distributions of r_T and r_B. The statistical analysis of clearance measurements for the sorting plant in Ranstad (Norberg 2012) contains a description of how the net count rate can be simulated given separate background measurement. The following description assumes paired measurements instead, even though the analysis can also be applied to total count rate.

For objects where contaminated areas have not been found during the survey, the normal distribution is probably a good model for net count rates, but if there are large variations in the contamination's spatial distribution, it may be better to assume log-normally distributed net count rates. Furthermore, the spatial distribution of measurement values may have to be analysed to identify any correlation between measurement values and position. If data for instance show increasing measured values along a certain space coordinate, there is reason to suspect that there is a point along this coordinate where the sum criterion could be exceeded. However, this should already have emerged during the radiological survey. In cases where data is not normally distributed, a division of the object into smaller subareas should be considered.

Estimates of the mean value and standard deviation (x and s_x) can be calculated from measured net count rates. For normally distributed net count rates, r_N can be calculated according to Equation 8-3 and the net count rate, and for a particular observation, ρ_N can be calculated according to Equation 8-4. P95 can be calculated/simulated from the latter expression.

8.3.4 Uncertainty in the nuclide vector

The nuclide vector is in this case assumed to be defined as the activity of every nuclide in proportion p_i to the total activity. For nuclide-specific clearance measurement, the nuclide vector is often defined as each individual nuclide's activity in proportion to the activity of one or more key nuclides, but the analysis of uncertainty in the proportions can be done in the same way.

Furthermore, the nuclide vector is assumed to be determined for a number of samples where the activity of occurring nuclides has been determined with sufficiently high accuracy that the uncertainty in individual measurement values will not affect the nuclide vector (the variation in proportions is assumed to be larger).

The uncertainty in proportions can be described with a Dirichlet distribution that considers $\sum_i p_i = 1$, but in order to use the Dirichlet model, some form of assignment of the error for at least one of the proportions is required, which is not trivial. It is also possible to simulate the uncertainty in each individual nuclide's activity relative to a key nuclide.

This report, however, suggests determination of the value of the clearance constant b_R for each sample. An estimation of the mean value and standard deviation of b_R can then be calculated from the samples taken, and b_R can be simulated based on one of the uncertainty distributions in Section 8.3.1.

8.3.5 The clearance product

For simulation of the clearance product, each of the parameters is simulated according to the description above, to then form the simulation $\gamma_D r_N b_R$. γ_D and b_R are simulated according to Equations 8-3 and 8-5 for normally or log-normally distributed parameters. The same holds for r_N when calculating UCL, but for the calculation of P95, ρ_N is simulated according to the distribution for an individual value (Equations 8-4 and 8-6).

8.4 Simulation

This guideline proposes simulation of the combined uncertainty through Monte Carlo simulation. This means that values from uncertainty distributions are sampled randomly repeated times. The value that corresponds to the 95th percentile of all simulated values provides UCL95 or P95, depending on which uncertainty distributions are being simulated. This determination of limit values also has some uncertainty depending on the simulation's extent. In order to minimise this uncertainty, the number of values should be large ($>10^5$) and several simulations with different random seeds should be carried out in parallel. By comparing the results of simulations with an increasing number of values and different random seeds, it is possible to ensure that the uncertainty in simulated limits does not affect the clearance result.

In order to assess the uncertainty in a simulated value, it is possible to calculate an upper confidence interval for the simulated limit with the same parameter-free methodology as proposed in Section 8.3.1.

8.5 Sampling strategy for clearance measurement

In order for the statistical methodology to be applicable, the measurements must be independent and equally distributed. This means that targeted sampling or sampling according to a predefined pattern undermines the statistical analysis. Independent and equally distributed measurements can be achieved by choosing the measurement location randomly within a part of an object. This can sometimes be considered problematic, since randomly selected measurement points risk giving poor coverage of the object area. In order to overcome this problem, a stratification of objects is proposed (see Figure 8-1), so that measurement is done in each subarea (strata), but randomly within these (SS-ISO 11932 (SIS 1997)). By dividing the object into smaller areas and ensuring that each area is measured, better coverage is achieved.

8.5.1 Combining data from different sampling occasions

Clearance measurements may be repeated for certain objects, for example to reduce uncertainty in net count rate and thus be able to clear the object. If the measurements are conducted in a similar manner and the measurement points are equally distributed and independent in all cases, the statistical analysis can be based on the total amount of data.

8.6 Uncertainty for individual measured values

Since the requirement for clearance is that the sum criterion is fulfilled for each square metre, individual measured values that are likely to derive from contamination exceeding the sum criterion must not occur. Therefore, uncertainty must be determined for each individual measured value. The Clearance Manual proposes so-called operative limits for clearance measurements defined as the clearance level minus the standard deviation s in the individual determined activity multiplied by 1.645. However, applying this requirement for all measurements is somewhat conservative. Instead, the following is proposed for individual measured values:

- Measured values where $\gamma_D \rho_N b_R \leq 1 - 1.645s$ are not likely to exceed the clearance condition (are always accepted).
- Measured values where $\gamma_D \rho_N b_R > 1 + 1.645s$ are very likely to exceed the clearance condition (the activity must always be removed). Clearance measurements should be interrupted and resumed after decontamination.
- Measured values where $1 - 1.645\text{s} < \gamma_D \rho_N b_R \leq 1 + 1.645s$ can be accepted, but the contamination should be removed if possible by simple means. Clearance measurements can be completed and analysed before decontamination.

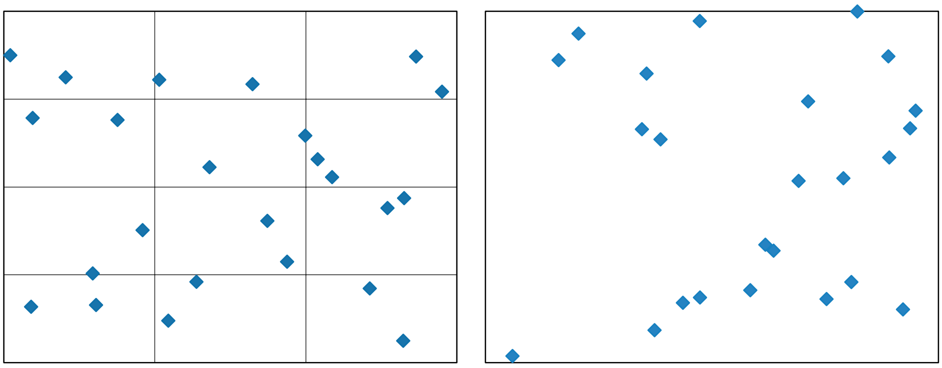

Figure 8-1. *Schematic illustration of stratified and non-stratified random selection. By ensuring that each square is sampled, the risk of missing large areas in sampling is reduced.*

The standard deviation cannot be easily calculated and the simulation procedure proposed for evaluation of measurement data (Section 8.4) will be unmanageable for each individual measured value. In this case, it is possible to use the approximation that is recommended in SS-ISO 11929:2010 (SIS 2010):

$$s_f^2 = \sum_i^n \left(\frac{\partial f}{\partial x_i}\right)^2 s_{x_i}^2 \tag{8-7}$$

where s^2_f is the variance for a function $f(x_1, x_2, ..., x_n)$ and s^2_x the variance for the variable x. The variance for ρ_N is determined from the number of measured pulses n_B and n_T and the measurement time t_B and t_T for background and total count rate measurement (Gilmore 2008) according to

$$\rho_N = \frac{n_T}{t_T} - \frac{n_B}{t_B}$$

and

$$s_{\rho_N}^2 = \frac{n_T}{t_T^2} + \frac{n_B}{t_B^2}$$

The combined uncertainty for the sum (s_i) according to Equation 8-7 can then be calculated as

$$s_i^2 = (\gamma_D b)^2 s_{\rho_N}^2 + \left(\frac{\rho_N b}{n_\gamma}\right)^2 s_{\gamma_D}^2 + \left(\frac{\rho_N \gamma_D}{n_b}\right)^2 s_b^2$$

where the first term contains the variance for the individual count rate measurement, while the two last terms contain the variance of the mean value for detector efficiency and the clearance constant that is estimated from n_γ and n_B measured/determined values.

8.7 Assessment of the occurrence of anomalies

In the context of random clearance measurement of radioactivity for larger objects such as buildings, it is natural to pose the question whether one can be sure that no pointwise source of radioactivity has been missed. Such sources are often called *hot spots*. Here we choose to call them anomalies since they correspond to a presence of activity, which greatly deviates from the overall distribution of activity.

In order to handle the issue above, it is possible to use statistical methods for assessing the risk of anomalies. By assigning a size and geometry to the anomaly, it is of course possible to make an assessment of the risk of occurrence, based on how large a portion of the object area was covered by clearance measurements. However, it is difficult to make a reasonable assessment of the size of an anomaly, since radioactive contamination with relatively high activity may nevertheless be small. This report therefore recommends a statistical analysis where the anomaly can be arbitrarily small.

If q_A is the probability that there are one or more anomalies, we can assume *a priori* that it follows a beta distribution beta (1.1). This is a uniform distribution on the unit interval (0.1), i.e. all values of q_A are equally probable.

After measurement where f is the number of identified[3] anomalies among n completed measurements, the following applies[4]:

$$q_A \sim \text{beta}(1+f, 1+n-f)$$

If anomalies are identified, the activity should of course be removed and repeated clearance measurements carried out. The analysis of the final result of clearance measurements will reasonably most often yield $f = 0$. The probability of occurrence of anomalies is therefore given by

$$q_A \sim \text{beta}(1, 1+n) \tag{8-8}$$

It is not possible to specify an individual value of the probability that there are anomalies, in the same way as it is not possible to say anything about for instance the highest conceivable net count rate. For the net count rate, it is possible (as discussed in Section 8.3) to specify how probable it is that the mean value (or the value of a new measurement) is below a predefined limit, or, which limit corresponds to a certain credibility (for instance UCL95 and P95). Statements concerning the occurrence of anomalies must in the same way be given in relation to a fixed limit for q_A or credibility. For example, we can specify the risk level (the value of q_A) given some pre-defined credibility, for example 95 %, or we can, for a given risk level (for example 5 %), specify the credibility that this is not exceeded.

Concerning the sum criterion, there is a specified limit, and we can show that this limit is maintained with a certain credibility. No such limit is defined for q_A. Therefore, we suggest that the credibility for q_A=5 % and the risk level for a credibility of 95 % are presented as a complement to the remaining statistical analysis and that reasonable levels for these values are determined in consultation with SSM.

If two objects are measured with the same number of measurements, the risk level will be the same (if no anomalies are detected), since Equation 8-8 yields that q_A then only depends on the number of measurements (see Figure 8-2). If the objects are of different sizes, however, the risk of anomalies cannot be said to be similar. In other words, the risk level must be put in proportion to the object's or subarea's surface area. The interpretation should be that a risk level on for example 5 % means accepting that 5 % of the object's area may have elevated levels. Whether this risk level is acceptable or not depends on how large the total area of the object is. Furthermore, the risk categorisation from the radiological survey should be considered in the assessment. A large object with previously identified contamination above the clearance level should have a much lower risk level than a small object deemed to have only *small risk of contamination*. Furthermore, this analysis can be supplemented with measurements to determine an upper limit for potentially occurring anomalies (see Section 7.2.2).

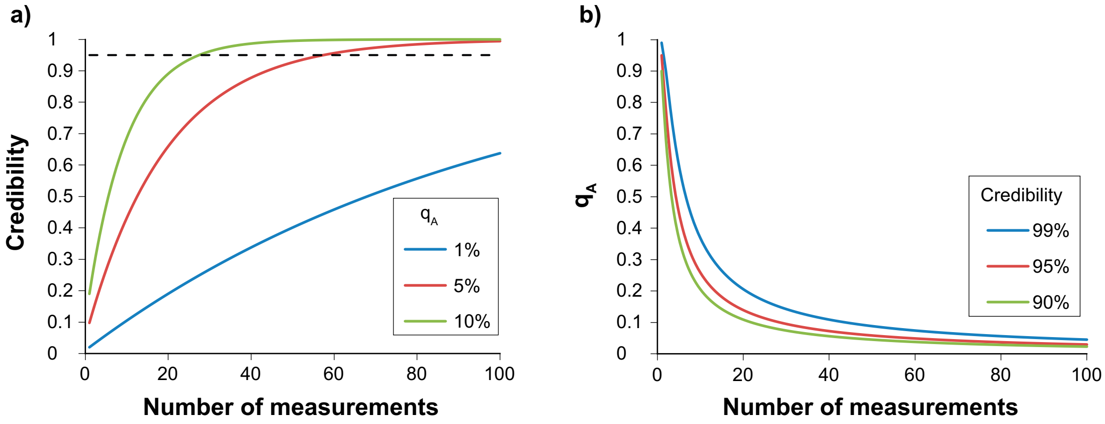

Figure 8-2. *a) Credibility as a function of the number of measurements for q_A = 1 %, 5 %, and 10 % (the dashed line indicates 95 % credibility), and b) q_A as a function of the number of measurements for 99 %, 95 %, and 90 % credibility. In all cases an outcome where no anomalies were encountered is assumed.*

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[3] Anomalies can be identified as measured values that, given the uncertainty distribution of other measured values, appear very unlikely (see the methodology described in Section 8.3.1).

[4] Here it is assumed that the probability of encountering an anomaly is constant and that the outcome of the measurements (with respect to the occurrence of anomalies) then follows a binomial distribution.

9 Control programme

The control programme shall, according to SSMFS 2011:2 (SSM 2011), contain information on methodology and extent of checks for radioactivity, who is authorised to perform the checks and information on quality assurance, self-assessment and documentation. For buildings, rooms, land or material quantities over 100 tonnes per calendar year, the control programme shall be submitted to SSM before activity checks are performed.

The control programme, produced by each licensee for the own facility, shall

1. describe the methods for and extent of the checks, i.e.
   a. what components, building parts, land and other objects will be inspected,
   b. when the measurements will be performed and the prerequisites for these measurements,
   c. the extent of measurements,
   d. the measurement methods, instructions and procedures that will be used in execution of the measurements,
   e. guidelines for extended checks or other actions in case of unexpected deviations from the expected measurement results (see Section 8.6 and 10.3.3).
2. state who is authorised to conduct the checks, and
3. contain information on quality assurance, self-assessment and documentation of results.

The work of preparing a control programme can preferably be started early in the clearance process, so that it can be ensured that survey measurements are of sufficient quality to be reused for clearance measurement. However, the control programme should be submitted only after completed survey and decontamination. The results from the radiological survey can then be described in general terms, with reference to separate documents where survey, decontamination and categorisation are presented in detail.

If the control programme is instead submitted early in the clearance work, all the results from survey and categorisation will not be available. The control programme will then have to describe the principles for both clearance measurement and the clearance process in its entirety (including radiological survey, categorisation and decontamination). The control programme will also need to be designed in a more general manner to cover all situations that may arise during the survey and decontamination work. References to work instructions should be given to provide detailed information on for example sampling strategy, measurement methods, etc.

In an appendix to the Clearance Manual, a proposal for a control programme is presented. The following is a supplementary description of the information that should be presented in the control programme for clearance in conjunction with dismantling and demolition.

9.1 Activity description

The activity description should present the operating history and events during operation that affect clearance on a general level. It should also describe the extent of the control programme regarding the objects that will be subject to clearance measurement. Thereafter, the different stages in the clearance process should be described. The focus should be on clearance measurement with associated analysis of measurement data.

9.1.1 Radiological survey, categorisation of objects and decontamination

If the control programme is prepared early in the process, it should present the methodology that serves as a basis for the survey. The principles for risk categorisation should be described as well as how objects in each risk category will be handled. It should be made clear how risk categorisation is established and documented. Decontamination methods should be described in general terms, particularly with respect to how the risk of dispersion of contamination will be handled. References to work instructions for the constituent steps should be given.

If the survey has already been completed, a description of how the radiological survey was conducted should be included instead. The results of the different stages are presented in general terms with reference to separate reports.

9.1.2 Determination of activity

Methods and procedures that will be used for clearance measurement of radioactivity prior to clearance shall be presented. The description should be general with references to work instructions, method descriptions and standards.

Sampling strategy

The distribution of measurement and sampling points should be described for each measurement method, as well as to what extent measurement and sampling will be carried out. If the radiological survey is already completed, the sampling strategy can be described in detail. Otherwise, the principles for how the sampling strategy is adapted to the radiological survey should be described.

Smear tests

The extent and assessment of smear samples taken in connection with clearance measurement should be described. Requirements on measurement equipment as well as the sampling and analysis procedure should be described with reference to work instructions and standards.

The purpose of smear tests is primarily to show that loose contamination has been removed in accordance with SSM's general advice for 7 § in SSMFS 2011:2 (SSM 2011). Removal of loose contamination and verification of the results of remedial action should be completed before clearance measurements begin. In such cases, there should be a report or a protocol from the remedial action that can be referred to.

Checks with count rate equipment and gamma spectroscopy

During clearance measurement, both count rate measurement and gamma spectroscopy are likely to be used. Requirements on measurement equipment, sampling and analysis procedure should be described with reference to work instructions and standards. The use of count rate measurement for activity checks should be justified based on the estimated nuclide vector.

Determination of nuclide vectors

Determination of nuclide vectors that will be used for clearance with nuclide-specific clearance levels shall be described. The section should include:

- a list of nuclides, which if necessary also explains why certain nuclides are excluded,
- sampling method and extent,
- analysis methods.

In cases where nuclide vectors have already been determined, the results can be presented briefly with reference to the previously prepared report.

Checks for the distribution of activity

It should be clear from the control programme if, and if so which, other measurements and analyses will be applied to ensure that the distribution of activity was sampled/measured to a sufficient extent (see Section 7.2.2).

It should also be described how activity checks will be conducted to determine the activity levels in fractures and on other surfaces that are difficult to access, and how the possible penetration of activity in porous materials will be checked.

9.1.3 Evaluation

The statistical methodology that will be used for evaluation of results from each method for determination of activity, shall be presented in detail or with reference to separate method descriptions. The criteria that will serve as a basis for clearance must also be defined here (see Chapter 8).

9.2 Management

Cleared objects will need to be managed after clearance to ensure that they are not contaminated again. Some objects might be interim-stored before final removal. Buildings, rooms and land will need management before conventional demolition. The measures that will be adopted to prevent recontamination during this period should be presented.

9.3 Applicable regulations and special decisions

The conditions for clearance should be specified in the control programme. For clearance of land, references should be given to the material used for derivation of clearance levels and decisions on future land use.

9.3.1 The regulation SSMFS 2011:2

It should be clear what specific paragraphs in SSMFS 2011:2 (SSM 2011) that are relevant for clearance according to the control programme. Here, it should be stated whether the clearance decision is taken by the licensee or SSM.

9.3.2 Special decisions

In the cases where clearance is done with other clearance levels than those given in SSMFS 2011:2 (SSM 2011), or if other exemption has been given from the regulations in SSMFS 2011:2 (SSM 2011), this must be reported with references to available documentation and the decision by SSM.

9.4 Quality assurance

Measures taken to ensure the quality of measurement, evaluation and documentation in conjunction with activity checks shall be described in the control programme. References should be given to work procedures and management systems.

9.4.1 Management system

It should be explained how the control programme is incorporated in the management system or if the management system contains references to ensure that the control programme is followed. Reference should be given to the parts of the management system that will be used for measurement, evaluation, documentation and decision on/application for clearance.

9.4.2 Procedures for self-monitoring and independent inspection

The self-monitoring that will be carried out and which steps in the monitoring that will be reviewed (sampling, analysis, documentation, etc.) should be presented. It is also appropriate to here describe independent inspections (see Chapter 10) and how large deviations that can be tolerated when comparing measurement data (for example by specifying a confidence level for significance testing).

9.4.3 Management of deviations

In connection with clearance measurement, it is possible that deviations from the control programme will occur and there should be procedures for managing such deviations. It should also be described how deviations identified for example in conjunction with self-monitoring will be managed.

9.4.4 Authorisation

Authorisation and description of the roles that occur in connection with clearance measurement shall be described in this section (see Chapter 10 and the Clearance Manual).

9.5 Documentation

Documentation constitutes the basis for clearance or an application for clearance. Furthermore, there are requirements that the documentation should be saved for 10 years after the decision on clearance. The control programme should describe what documentation will be developed in connection with clearance measurement and what other documents will be included in the basis for clearance (see Section 10.3.4).

9.5.1 Reports

To make decisions regarding clearance or apply for clearance at SSM, a clearance report needs to be developed that summarises the work and results of clearance measurements according to the control programme. As a basis for this report, the following are used:

- Drawings and description of objects.
- Documentation on determination of nuclide vectors.
- History and survey report.
- Calibration/verification documentation for measurement methods.
- Measurement protocols.
- Review documents.

9.5.2 Storing of data

For larger objects, large amounts of measurement data will be generated. Measurement data include time and location specifications, measured values and information on equipment, contractors etc and are preferably stored in a database. The data stored in conjunction with measurements and the format used for storing data should be presented (see Section 10.3.4).

9.5.3 Archiving

The control programme should specify how and which documentation will be archived. Archiving is required to ensure the preservation of documentation for 10 years from the decision on clearance (see Section 10.3.4).

10 Quality assurance

A fundamental requirement in SSMFS 2008:1 (SSM 2008) is that each licensee must have both the organisation that is required for the nuclear activities (including decommissioning) and the management system that is required to lead, control and procure these activities. The implementation of the management system, its suitability and efficiency will be reviewed systematically and periodically by an audit function for analysis and improvement of the activities. The audit function must have an independent position in relation to the activities that will be subject to review. Furthermore, there must be an established audit programme at the facility. Quality assurance of all clearance is thus also a part of the licensee's management system, with requirements on audits and monitoring. Any deviations during the clearance process should be discussed in quality meetings together with those responsible for the management system, where decisions on corrective actions are taken.

The licensee should also establish an expert group that continuously follows the clearance process, inspects the measurement results and solves any resulting measurement problems. At each expert group meeting, minutes are recorded and saved in the documentation system. The expert group could consist of representatives from project management, supervisors for the measurement group and an expert in, for example, radiochemistry, radiophysics, and statistics.

Following a well-defined procedure, also for quality assurance, should entail greater cost-effectiveness overall, which makes it easier to keep to the established timetable. This reduces the risk of unforeseen events and thereby also the risk of unforeseen added costs. Additional advantages are increased safety and a higher confidence in the rest of the world.

For clearance, requirements are made in accordance with SSMFS 2011:2 (SSM 2011) that quality assurance during clearance measurements shall be described in the control programme. There are therefore reasons to provide specific recommendations for how quality assurance should be performed, from preparation of the control programme to clearance measurement, documentation and decisions on/application for clearance, since these parts of the clearance process are governed by the regulations.

Initial assessment, radiological survey and decontamination are not regulated specifically in SSMFS 2011:2, and there is thus no specific requirements on quality assurance. The quality assurance that follows from the licencee's management system for similar work tasks should be sufficient.

The objective of this chapter is to describe how the clearance process can be quality assured during dismantling and demolition of nuclear facilities, i.e. how process flow can be controlled in order to minimise the risk of mistakes. The content should be regarded as a development of Chapter 8 (Quality assurance and documentation) in the Clearance Manual (SKB 2011), which mainly deals with quality assurance for clearance of components and materials.

The regulation SSMFS 2011:2, 8 § includes requirements on quality assurance and self-monitoring for clearance. It is important to meet these requirements, so that neither SSM's nor public confidence in the activities is damaged through incorrectly conducted clearance. Self-monitoring in this context means monitoring carried out in own activities (also for external actors) and with own responsibility, i.e. peer review and approval of instructions, testing protocol, reports, etc. Other forms of monitoring activities that are discussed in this chapter are independent inspection, i.e. an inspection activity that is not directly involved in the clearance process. Independent inspection refers to an inspection performed by competent resources either within the licensee's own organisation or an impartial inspection that is carried out by an external competent resource.

There is no tailored quality management system for clearance during dismantling of a nuclear facility, since there have been few projects of the type in Sweden. But there are several aids and recommendations for how testing activities can be quality assured. Among the most important are ISO 9001:2008 (ISO 2008) and ISO 17025:2005 (ISO 2005). They are discussed in more detail in Section 10.1 below.

10.1 ISO standard for quality assurance, certification and accreditation

ISO 9001:2008 (ISO 2008) defines requirements on management systems for quality and states that the organisation or project should be based on the customer's or SSM's requirements and consider internal work methods for more efficient work flows. ISO 9001:2008 should serve as a basis for quality assurance in clearance during dismantling and demolition of nuclear facilities. This is also true of the licensee's own management system. See Section 10.2 below.

ISO 17025:2005 (ISO 2005) is a standard for quality control of testing and calibration laboratories. The standard is divided into two parts, one for requirements on the management system (basically ISO 9001:2008) and one for technical requirements, like technical competence, premises, environmental conditions etc.

The certification entails a formal process where an accredited certification body assesses for example a laboratory and issues a written statement on their general competence and activities.

Many organisations that use external laboratories demand that the laboratory is accredited according to ISO 17025:2005. Accreditation means that an accreditation body assesses a laboratory with respect to a defined type of check or measurement and gives a formal recognition of its competence in this area. The accreditation process aims to increase the reliability of results from testing and calibration, and to make it easier for customers to choose reliable testing, measurement and calibration services. In Sweden, this means that the accreditation body SWEDAC (Swedish Board for Accreditation and Conformity Assessment) assesses the laboratory, or that the laboratory is assessed by a foreign, internationally recognised accreditation body.

Accreditation means that laboratories can prove their competence and that they have functioning quality assurance, and is a proof of technical competence and independency. Regulatory authorities or other procurers, such as industries or county councils, in some cases demand accreditation in order for laboratories to perform certain types of testing/calibration.

ISO 17025:2005 is used for assessment of laboratories all over the world, factors that are regarded as relevant for the laboratory's technical competence are:

- Technical competence of personnel.
- The laboratory's independency.
- Validity and adequacy of testing and calibration methods.
- Traceability of measurements and calibrations.
- Adequacy of equipment and its maintenance.
- Environment for testing and calibration.
- Collection, handling and transport of samples, material, instruments etc.
- Quality assurance of testing and calibration data.

Even if a laboratory meets the requirements in ISO 17025:2005, it does not automatically mean that it also meets the requirements in ISO 9001:2008, this requires a separate certification of the laboratory in question.

If there is any advantage, for example technical, economical or logistic, of engaging accredited laboratories should be considered from case to case, if there is access to such companies for the requisite clearance measurements or other analyses in the clearance process.

10.2 Management system

10.2.1 Scope

According to ISO 9001:2008 (ISO 2008), a management system considers all activities in an organisation that affect the quality of a product; in this case the clearance data. The management system is built up as the licensee's corporate management prescribes policies, goals and procedures for the clearance work.

Fundamental requirements for the licensee's organisation, management and control of nuclear activities are given in SSMFS 2008:1 (SSM 2008). The following is a brief summary of the most important parts that should be included in the licensee's management system, with respect to the clearance process (see also the introduction to Chapter 10 above):

- Control of documents: The documents in the management system are built up based on a number of requirements, such as traceability, distribution and validity.
- Management commitment: This part determines and describes how responsibility, policy, goals, communication and management review are managed.
- Management of resources: In order for a management system to function, it is important that relevant resources, such as personnel with the right skills and infrastructure, are allocated.
- Product preparation: This part establishes all requirements that directly concern the preparation of clearance data such as planning, control programmes, execution of measurements, results of evaluations, self-monitoring, reports and storage of data.
- Monitoring, measurement, analysis and continuous improvement: This part deals with internal audits, monitoring and measurement of processes, deviations as well as preventive and corrective actions.

Since the clearance process may require involvement of external resources to a large extent, for example to perform measurements and analyses, it is a requirement that the external companies engaged by the licensee have their own, approved management systems based on applicable parts of ISO 9001:2008 and ISO 17025:2005 (ISO 2005), unless they are included in the licensee's own organisation and work under the licensee's management system. This does not, however, release the licensee from the main responsibility for the quality of the externally delivered service (See also Section 10.4 below).

10.2.2 Management responsibility, quality policy, planning, authorities, communication and quality meetings

The licensee has a legal responsibility that the clearance process is conducted in a correct and error-free manner. It is therefore important that the management declares a quality policy for the process in writing. The quality policy can be included in the licensee's management system for the entire dismantling and demolition process, but can also be created separately in order to emphasise that clearance is an important part of this process. The clearance data will serve as a basis for clearance of the facility. The role of management is also to establish the focus on quality with all involved organisations and personnel.

10.2.3 Infrastructure and operating environment

Infrastructure

The licensee should together with project management already in the planning stage make sure that there is access to infrastructure in the form of monitoring equipment, auxiliary material and laboratory capacity. The infrastructure that is necessary to carry out the activities while assuring quality should be specified in the control programme. This may entail that the licensee already in the planning stage prior to dismantling and demolition must inventory the availability of suitable contractors that meet stipulated requirements, and if necessary establish the contacts required to create these conditions. See also Section 10.1 above.

Operating environment

It is important to ensure the requirements on operating environment, especially when sampling, testing and/or calibration is performed elsewhere than in permanent laboratories, so that the results do not become invalid due to environmental conditions and that these conditions do not affect the quality of measurements in an unfavourable manner. Requirements on a suitable operating environment are also specified in ISO 17025:2005 (ISO 2005), Section 5.3.

The licensee, together with project management, should make sure that the personnel are working in a physical and psychosocial work environment in accordance with the Working Environment Act (SFS 1977:1160) and the Radiation Protection Act (SFS 1988:220).

10.3 Quality assurance during the clearance process

Generally, the process flow can be described in six stages according to Figure 10-1 below, depending on what will be cleared. The difference is mainly that clearance of buildings, rooms and land shall be determined by SSM.

The following sections, 10.3.1 to 10.3.5, present a proposal for how quality assurance can be managed in each step of the clearance process according to Figure 10-1 below.

Before the control programme can be devised it is often necessary to conduct a radiological survey and preliminary risk categorisation of the facility (see Chapter 3), in order to determine the extent of the control programme on the basis of preliminary measurements and facility history. This process is concluded with a survey report that is managed according to the licensee's management system, and reviewed and approved internally by personnel that are well acquainted with the historical activities in the facility and have good knowledge in radiophysics and/or radiochemistry. The documentation from the radiological survey, including performed measurements, is managed to a suitable extent in accordance with Sections 10.3.3 and 10.3.4 below.

10.3.1 Control programme

In order to ensure that the written control programme and its extent corresponds to the requirements in SSMFS 2011:2 (SSM 2011) 8 §, review and approval can be carried out in the following steps:

- A documented peer review of the scope and content of the control programme and that the control selection is correct, and that the licensee has followed established principles, methods and approaches for its preparation. The peer review is carried out by an authorised individual, that did not participate in the preparation of the control programme, and that has sufficient competence to review it, i.e. Good Knowledge (GK) of the discipline according to the competence requirements in Section 10.4 below.
- After the peer review, there is an independent review of the control programme and control selection, which focuses on if the licensee has followed established principles, methods and approaches for preparation of the control programme, including the peer review, and that the conclusions and decisions made are reasonable. The review can be carried out by an independent resource with Good Knowledge (GK) of the discipline according to the competence requirements in Section 10.4 below.
- Thereafter, the control programme is approved by an authorised manager within the unit that developed the control programme and control selection, or a responsible project manager for the sub-project concerned.

After approval of the control programme and control selection, they are submitted to SSM, if required according to the conditions in SSMFS 2011:2 8 § and each licensee's standard procedures for such cases.

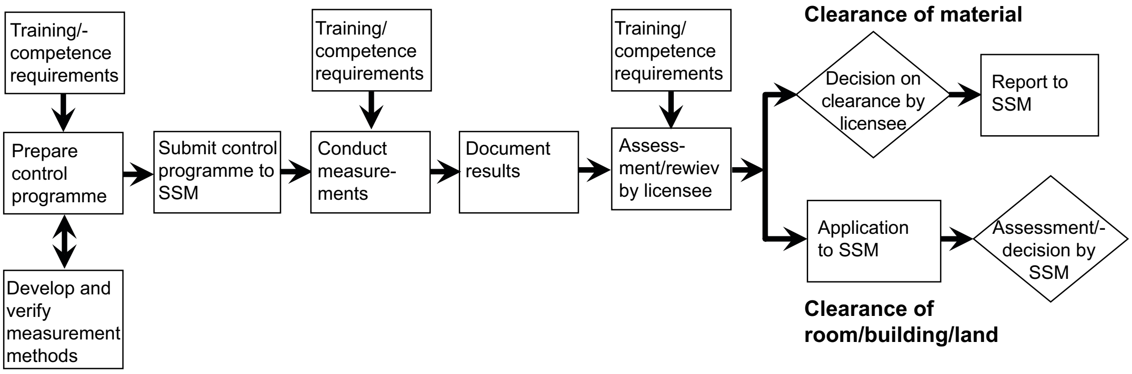

Figure 10-1. Process flow for clearance of material, room, buildning and land.

10.3.2 To develop and verify measurement methods

Premises

The measurement methods and the extent of the check should be adapted to the estimated presence of radioactive contamination and to the properties of the material, room, building or land, and be in accordance with Swedish or international standards or guidelines that have been decided by SSM (see Chapter 7).

It is important to, as far as possible, select measurement methods that are

- based on standardised procedures,
- have been used for a long time with documented experience,
- practically applicable.

For each measurement method, there should be a procedure (instruction) that states application area, conditions for measurement, competence requirements, necessary equipment and calibrations, how the measurement is performed, acceptance levels and how results and any deviations are documented and reported.

Measurement methods – verification

To confirm that the results obtained in clearance measurements are correct and corresponds to the requirements on accuracy, applicable measures should be taken and documented according to ISO 17025:2005 (ISO 2005) Section 5.4.5. The technology that is used to determine the performance of a method should be one of or a combination of

- calibration of measurement instruments using standard radiation sources,
- comparison with results from other measurement methods,
- systematic assessment of factors that affect the results,
- estimation of the uncertainty in results based on the principles of the method and practical experience.

Verification of a measurement method should be carried out by an authorised individual with competence requirements for Reviewer according to Appendix 9 in the Clearance Manual (SKB 2011) and approved by an authorised individual with competence requirements for Approver (GK) according to the same Appendix. The verification of the measurement method is attested by the instruction being signed by both of these functions, and can be carried out within the licensee's own organisation. Thereafter, the approved measurement method with the associated instruction is ready to be used.

10.3.3 Conducting measurements

The following description mainly deals with quality assurance for clearance measurement, but may also be applied to as far as possible ensure the quality of measurements in conjunction with radiological survey.

Premises

The measurements can either be performed by the licensee or by an approved contractor, which reports to the licensee. One reason for choosing the latter alternative may be the large quantities of material, components and building volumes that are managed and cleared during a relatively brief period in conjunction with dismantling and demolition.

The control programme should accurately define competence requirements on personnel who will carry out measurements, evaluations of measurement results and who are authorised to make model calculations. Requirements for competence of contractors is described in SSMFS 2011:2 (SSM 2011), 17 § and the Clearance Manual (SKB 2011), Chapter 9 (Competence requirements and training). Competence requirements for personnel at external organisations engaged by the licensee can be found in relevant parts of ISO 17025:2005 (ISO 2005), Section 5.2.

For model calculations and evaluations of gamma spectroscopy measurements, Good Knowledge (GK) is required in both radiophysics and/or radiochemistry as well as long experience from similar projects. Evaluation of routine gamma measurements can be made by personnel with lower competence levels, provided that the results are reviewed by personnel with Good Knowledge.

Quality assurance of clearance measurements

All clearance measurements are carried out by personnel with sufficient experience of radioactivity measurements (see Section 10.4 below). Each evaluation of measurements should be reviewed by at least one additional authorised individual with competence requirements for Evaluator according to Appendix 9 in the Clearance Manual. The review also includes verifying that all input data agree with the measurement results and to release the measurement results.

All handling of measurement instruments is documented in the form of instructions that are reviewed and updated when necessary. Measurement equipment should in relevant parts meet the requirements in ISO 17025:2005, Section 5.5.

The traceability of measurements and quality assurance of testing and calibration results should in relevant parts meet the requirements in ISO 17025:2005, Sections 5.6 and 5.9.

If the contractor that is engaged for clearance measurement is accredited with respect to a defined type of check or measurement, according to the requirements in ISO 17025:2005 (see Section 10.1 above), the contractor is also solely responsible for quality assurance of their results, and in that case no further action from the licensee is required. Signed measurement protocols and reports from performed clearance measurements are thereby sufficient documentation.

Otherwise, at recurrent intervals (as is evident from the control programme), random quality checks should be conducted by an independent inspector with competency requirements for Evaluator according to Appendix 9 in the Clearance Manual (SKB 2011). The inspector's task is to check that the regular measurements are carried out in accordance with the control programme and the current measurement instructions, to perform clearance measurements and verify that measurement results from the same measurement point are equivalent. A decision on how large deviations can be tolerated when comparing measurement values should be made in advance, with knowledge of the measurement system's uncertainties (see Section 9.4.2). Even in these cases, signed measurement protocols and reports from performed clearance measurements are sufficient documentation. Any deviations should, according to the introduction above, be addressed in quality meetings with those responsible for the management system, where decisions on corrective actions are made. The results of the checks are reported and saved in the documentation system.

All measurement results are documented. If a measurement is repeated, both measurement results should be saved with comments on why the measurement was repeated.

In order to ensure that the measurements are performed according to the control programme, follow-up should be performed by an expert group according to the introduction above, which continuously follows the clearance process, controls the measurement results and solves any measurement problems.

10.3.4 Document results

Premises

The execution and result of a check should be documented. The documentation must be preserved until clearance has occurred and thereafter for ten years, or another time frame given by SSM (see § 9 SSMFS 2011:2).

For each measurement, the contractor documents the results in a measurement protocol. When all measurements have been carried out, the licensee presents and comments on the results in a clearance report for each sub-project. The clearance report summarises all the results obtained in measurements with reference to underlying control programmes, reports and measurement protocols.

Documentation and archiving

Requirements on a documentation system are described in ISO 9001:2008 (ISO 2008). The entire clearance process is very complex and it is extremely important to have a system that covers all necessary documentation. The standard ISO 9001:2008 imposes a requirement to have a controlling document (can be called instruction for document management) that describes both requirements and procedures for how documentation systems should be managed. The documentation system includes the quality policy, quality manual, control programme with all included procedures for the execution of measurements, evaluations, clearance approval and all measurement results produced during the process.

The controlling document should contain the following:

- All documents are reviewed and approved by an authorised individual before they come into force.
- All documents are inspected and updated (if necessary) in recurrent intervals.
- If the documents are updated, there should be a system that describes version status.
- Older versions should be archived so that they are not used in the clearance process by mistake.

The control document should also contain instructions for how measurement results, evaluations and documented clearance decisions should be archived. Archiving shall take place in a safe manner. Data should be easily accessible and linked to the right objects, and there should be no risk of mistakes.

Otherwise, the requirements for external actors according to ISO 17025:2005 (ISO 2005), Sections 4.13, 5.7 and 5.10 should be fulfilled in relevant parts.

It is judged to be completely necessary to collect all measurement data in a database. Measurement data should generally be stored in raw format, i.e. as they are measured and presented by monitoring equipment, in order to be processed in various analysis tools. All measurement data should, besides measured values, also contain information on time, position, equipment used, calibration, contractor, environmental conditions etc. See ISO 17025:2005 Section 5.4.7 and ISO 17025:2005 Section 5.10.

It is important to be aware of the fact that incorrect input is probably one of the most common quality deficiencies. The system should therefore have functions for the laboratory/contractor to register measured data directly into the system, which means that the licensee obtains the data directly in a database and does not need to import anything. However, this requires that all data are quality assured by the laboratory/contractor before they are registered in the licensee's system. Finally, a check is made that the registration of data in the licensee's database is correct (review according to the licensee's management system).

There should also be functions that warn of potentially incorrect data, for example large deviations (*outliers*), by comparing different data from the same measurement point with each other or warn of too large variations in adjacent measurement points. In addition, manual measures are required to correct any errors. There should also be functions for export of data to other systems and analysis tools.

Used correctly, a database can be one way for the licensee to present measurement data in its reports to regulatory authorities such as SSM.

Archiving can be done in a well-established (quality assured) database and/or in the form of paper documents. SSMFS 2011:2 requires that data is stored at least 10 years after clearance has occurred. It is important that all documentation, both paper documentation and electronic documentation, is quality assured and that reported measurement data are kept intact, so that they do not change in any unauthorised manner in the database or degenerate over time, for example become unreadable or unusable in newer computer systems.

10.3.5 Approval and clearance

Premises

The last stage in the clearance process is different depending on what is to be cleared, i.e. material/components, buildings or land, which can also be seen in Figure 10-1 above:

1. A decision on clearance of material and components can be made internally by the licensee's own organisation. Since large quantities (> 100 tonnes) are involved, the control programme should be submitted to SSM in advance. Clearance of more than 1000 kg of material per calendar year shall be reported to SSM in conjunction with the annual report.
2. A decision on other uses (than practices with ionising radiation) of rooms within the licensee's own activities can be made by the licensee.
3. A decision on clearance of buildings and rooms that will be sold or demolished is made by SSM after an application by the licensee.
4. A decision on clearance of land is made by SSM after an application by the licensee. The clearance levels for land are determined by SSM in each specific case.

All documentation, measurement protocols, model calculations and reports are saved in the licensee's documentation system. See Section 10.3.4 above.

Clearance of materials and components, and decisions on other uses for buildings and rooms

Clearance of materials and components requires as a basis a compilation of all measurement results, conclusions and a statement by a person with competence requirements corresponding to Evaluator according to Appendix 9 in the Clearance Manual (SKB 2011). The clearance decision is made by a person with competence requirements corresponding to Approver according to the same appendix. If the total amount of cleared material exceeds 1000 kg per calendar year, the results are reported to SSM together with the annual compilation reports.

If the total amount of cleared material exceeds 100 tonnes and if it required a separate control programme, reporting can be done in the form of a separate clearance report which, besides a summary of measurement results, also presents a description of measurement methodology and measurements performed.

Review and approval of the clearance report is carried out in the following steps:

- A documented peer review of extent, results and content of the clearance report in relation to the control programme that serves as a basis for it, including an assessment of the results and conclusions that are presented in the report. Peer review is carried out by a person that did not participate in preparation of the clearance report, and has Good Knowledge (GK) of the discipline according to the competence requirements in Section 10.4 below.
- After the peer review, the clearance report is approved by an authorised manager within the unit that developed the clearance report, or the responsible project manager for the sub-project concerned.

A decision on clearance of materials and components is made by an authorised individual at the licensee with Good Knowledge of the discipline according to the competence requirements in Section 10.4 below. See also Section 9.1.2 (Competence requirements and training) and Appendix 9 in the Clearance Manual.

The same procedure applies for buildings and rooms that in the future will be used by the licensee for other purposes than practices involving ionising radiation, and temporary clearance for rooms in buildings that will later be sold or demolished after a special clearance decision by SSM.

Clearance of buildings to be sold or demolished

Clearance of buildings that will be sold or demolished requires a separate report that describes building history, choice of clearance levels, measurement methods, conducted measurements, the calculation models used, measurement results, conclusions and a statement.

To ensure the scope and content of the report, review and approval of it can be carried out according to the proposal in the following steps:

- A documented peer review of extent, results and content in relation to the control programme that serves as a basis for the report and an assessment of the results and conclusions presented there. Peer review is carried out by a person that did not participate in preparation of the report and has Good Knowledge (GK) of the discipline according to the competence requirements in Section 10.4 below.
- After the peer review, there is an independent review of the report. The review can be carried out either by an independent function within the licensee's own organisation or by an independent external resource with good knowledge (GK) of the discipline according to the competence requirements in Section 10.4 below.
- Subsequently the report is approved by an authorised manager within the unit at the licensee that developed the report in question.

The formal application to SSM on clearance of buildings to be sold or demolished is managed according to each licensee's standard procedures for licence application.

Clearance of land

Establishment of clearance levels for land

The clearance levels for land are determined by SSM in each specific case. Practically, this entails that SSM decides on applicable clearance levels for land on a specific site, after an application from the licensee concerned. This requires a report that describes the land's history and future use based on probable scenarios as stated in Chapter 11.

In order to ensure the scope and content of the report, review and approval of it can be carried out according to the proposal in the following steps:

- A documented peer review of extent, results and content of the report and an assessment of the results, conclusions and standpoints presented in it. Peer review is carried out by a person that did not participate in preparation of the report and has Good Knowledge (GK) of the discipline according to the competence requirements in Section 10.4 below.
- After the peer review, there is an independent review of the report. The review can be carried out either by an independent function within the licensee's own organisation or by an independent external resource with Good Knowledge (GK) of the discipline according to the competence requirements in Section 10.4 below.
- Subsequently the report is approved by an authorised manager within the unit of the licensee that developed the report in question.

The formal application to SSM for establishment of clearance levels for land is managed according to each licensee's standard procedures for licence application.

Clearance decision for land

Clearance of land requires a separate report, which describes the land's history, choice of clearance levels, measurement methods, conducted measurements, the calculation models used, measurement results, conclusions and a statement.

In order to ensure the scope and content of the report, review and approval can be carried out according to the proposal in the following steps:

- A documented initial review of extent, results and content in relation to the control programme that serves as a basis for the report and an evaluation of the results and conclusions presented there. The review is carried out by a person that did not participate in preparation of the report and has Good Knowledge (GK) of the discipline according to the competence requirements in Section 10.4 below.

- After the initial review, there is an independent review of the report. The review can be carried out either by an independent function within the licensee's own organisation or by an independent external resource with Good Knowledge (GK) of the discipline according to the competence requirements in Section 10.4 below.
- After the reviewing, the report is approved by an authorised manager within the unit at the licensee that developed the report in question.

The formal application to SSM on clearance of land is managed according to each licensee's standard procedures for licence application.

10.4 Personnel resources

Before the clearance activities are started, project management should ensure that there is enough personnel with adequate training and experience. The competence level of personnel should at least correspond to the requirements made in SSMFS 2011:2 (SSM 2011), 17 §. If a subcontractor is engaged, the client shall ensure that the subcontractor has a management system according to ISO 9001:2008 (ISO 2008) and ISO 17025:2005 (ISO 2005) and that the personnel resources provided correspond to the client's requirements on training and competence. Competence requirements according to relevant parts in ISO 17025:2005 Section 5.2 also apply for external companies.

The requirements made on personnel should be described in detail in the control programme for clearance. These requirements are based on Chapter 9 (Competence requirements and training) in the Clearance Manual (SKB 2011), which specifies the following three roles:

Measures:	Conducts practical measurements based on instructions from work management.
Evaluates:	Evaluates or reviews measurement results and decides whether supplementary checks are needed.
Approves:	Makes a final assessment of the clearance case. Shold have good knowledge of the activities and activity system, but detailed knowledge of measurement techniques is not required.

For grading the competency requirements within the different disciplines, the following levels are used:

Awareness (Aw):	Means that the person is familiar with the discipline and knows where supplementary information can be obtained.
Knowledge (Kn):	Means that the person has insight into the discipline's function, build-up and application and knows where supplementary information can be obtained.
Good knowledge (GK):	Means that the person has insight into the discipline in its entire extent and also knowledge of its background and philosophy.

Appendix 9 in the Clearance Manual also contains proposals for competence profiles for the different roles in the clearance process.

10.5 Secondary processes

All measurement instruments used for the measurements should periodically be calibrated against certified standards, inspected and, if necessary, adjusted according to the relevant instructions. The instruments should be protected so that no unauthorised individual can alter their settings. Each calibration occasion, inspection and adjustment must be documented and added to the contractor's documentation system. These procedures should be incorporated into the contractor's management system.

The standard ISO 17025:2005 (ISO 2005) specifies in Section 5.5 the requirements made on the use of measuring equipment.

10.6 Analysis and improvements

According to the introduction above, the application of the management system, its suitability and efficiency should be investigated systematically and periodically by an audit function for analysis and improvement of the activities. This means that all in clearance constituent processes are analysed at regular intervals with respect to their functionality. The time intervals for these analyses are determined and documented in the management system. Each analysis should be documented and presented in quality meetings. Quality meetings determine actions if the analyses show deviations from the quality requirements and provide recommendations for improvement of processes. A detailed compilation of requirements and procedures on correction and improvement measures can be found in ISO 9001:2008 (ISO 2008), Chapter 8 and ISO 17025:2005 (ISO 2005), Section 4.11.

10.7 Other comments

For further support in addition to the recommendations in this chapter, it is possible to use relevant parts of the British nuclear industry's Code of Practice, Chapter 4 (SDF 2005) and Survey Manual, Chapter 4, (ORISE 2008), developed by Oak Ridge Institute for Science and Education. The content of these two reports are based on foreign (British and American) conditions, and therefore have not been considered in this chapter. They can nevertheless be useful when the licensees designs their quality management systems.

11 Derivation of clearance levels

11.1 Introduction

General clearance levels (clearance for unrestricted use) have been determined through analysis of scenarios and calculation of dose for selected scenarios. According to the IAEA (IAEA 2007), a scenario is *a postulated or assumed set of conditions and/or events. A scenario may represent the conditions at a single point in time or a single event, or a time history of conditions and/or events.* The choice of scenarios focuses on the individuals that are most exposed to radiation, the critical group. When deriving clearance levels for unrestricted use, a number of different scenarios were analysed and the assumptions in the scenarios are pessimistic, so as not to underestimate the dose. General clearance levels are therefore relatively restrictive.

Clearance for specific purposes is an alternative to general clearance. Clearance can then be carried out after a licence application, which demonstrates, with knowledge of the material, site and handling, that the dose to the public is acceptable. This can be achieved through analysis of scenarios and calculations of dose and dispersion in the same way as for preparation of general clearance levels. The limitations, which are specified in conditions, entail that fewer scenarios are possible, fewer exposure pathways need to be considered and pessimistic general assumptions can be replaced with more realistic values and site-specific data. Figure 11-1 presents a schematic illustration of the process for conditional clearance.

In order to show that the calculated doses for conditional clearance are credible, the following is needed (NRC 2006):

- Characterisation of the radioactive source term.
- Reasons for choice and design of scenarios.
- Account of the choice of parameter values.
- Account of mathematical model or code used.
- Analysis of uncertainties.

There are uncertainties in the selection and design of scenarios, models and data, so they should all be included in the analysis of uncertainties.

For land, the clearance levels determined by the Swedish Radiation Safety Authority apply in each specific case (SSM 2011). The application for clearance of land is preferably made with the methodology described above. SSM presently works with preparing rules for clearance of land. They are based on relevant parts of the methodology used by Naturvårdsverket (the Swedish Environmental Protection Agency) for calculation of guideline values for substances in contaminated land (Naturvårdsverket 2009), but adapted to the special exposure pathways that apply for radioactive substances.

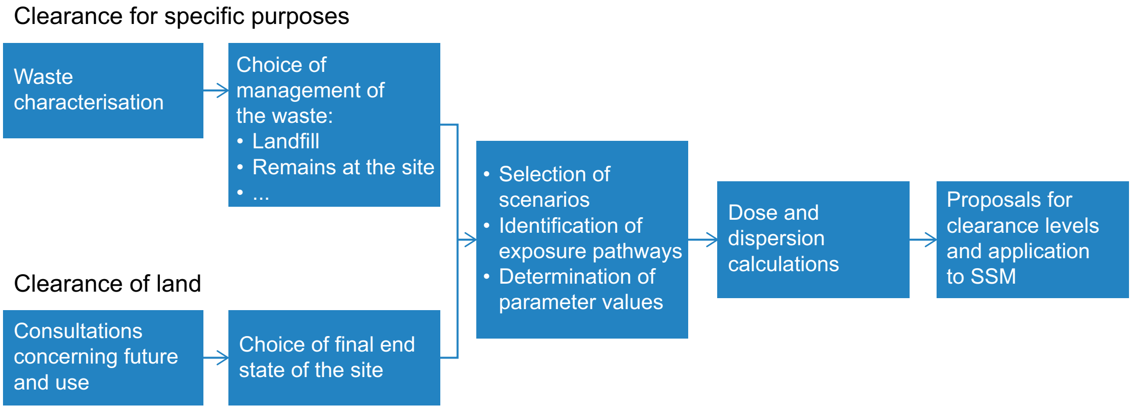

Figure 11-1. *Schematic illustration of the process for derivation of clearance levels.*

This chapter describes the exposure pathways that are considered in scenarios and how suitable scenarios and representative data are chosen to support clearance. An appendix to this report (Appendix F) presents the decommissioning of the sorting plant in Ranstad as an example of how the choice of scenarios and calculations of dose and dispersion was used to support the application for conditional clearance of materials (building materials, objects and other loose materials), for construction work on the site and for disposal in a landfill for hazardous waste.

11.2 Process for derivation of clearance levels

The process for derivation of clearance levels (Figure 11-1) can start independently of the process for clearance. For materials, buildings and land, suitable disposal options must be identified and the entire management from and including clearance must be described in detail. For land, the final state of the site and continued land use must be defined instead, which requires consultations with local stakeholders such as municipality and county administrative board. After this initial work, conditional clearance and clearance of land follows the same process of selection of scenarios and exposure pathways and gathering of site-specific data for the parameters included in dose and dispersion calculations. In this phase, the contaminated material's properties must also have been determined, but it is not necessary to have completed clearance measurements.

In connection with clearance, the concentration of radionuclides will be very low, probably well below the solubility limit. Thus the activity levels do not affect the chemical and physical processes that govern radionuclide transport. For this reason, it is not necessary to have completed clearance measurements in order to carry out the work with derivation of clearance levels. However, it is necessary to decide at an early stage what radionuclides need to be considered in the dose and dispersion calculations. If clearance measurements are not conducted until after clearance levels have been derived, it may also turn out that the object cannot (without extensive decontamination efforts) be cleared according to the derived clearance levels. From a cost and efficiency perspective, there is therefore reason to have a good idea of the object's degree of contamination before clearance levels are derived.

Decisions on applying clearance levels for land, or other clearance levels than those given in the regulations, are made by SSM. The application for a licence to apply derived clearance levels can be sent separately, or the results from dispersion and dose calculations can be submitted in conjunction with the application for clearance of a specified quantity of material.

11.3 Methodology for dispersion and dose calculations

The critical group in a scenario is exposed via one or more specified exposure pathways that are judged to be important. An overview of common exposure pathways is shown in Figure 11-2. Some important exposure pathways may also arise after the dispersion of material or radionuclides from the original site for the radioactive material. This section therefore presents the methodology for calculating dose via different exposure pathways and different dispersion pathways.

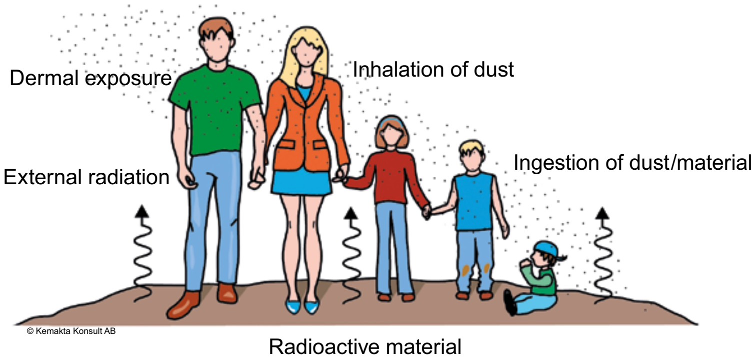

Figure 11-2. Examples of exposure that can arise from radioactive material, in this case land (courtesy of Kemakta Konsult AB).

11.3.1 General description of the methodology for dose calculations

External exposure

Gamma radiation and other photons emitted from radionuclides give rise to external exposure of individuals in the vicinity of a radioactive source. The size of the external exposure from a particular source depends on a number of factors such as

- size, shape and density of the source,
- radionuclides, activity, photon energy,
- distribution of activity in the material,
- distance to the exposed individual,
- occurrence of shielding,
- exposure time.

The size and shape of the source affects the radiation field in the environment and thereby how the dose rate changes with the distance from the source. The distance plays an important role, since radiation and intensity decreases with distance. A useful analogy is the heat from a fire, which also decreases with distance. A large fire provides heat at a larger distance than a small fire, in the same way the radiation field at a given distance is stronger if the source has larger dimensions.

Shielding between a radioactive material and an individual can reduce exposure by radiation absorption. Radiation energy is also lost by interaction with the material itself, and this is affected by the shape and density of the source. The distribution of activity is important, a material with shallow contamination emits more radiation than a material with a homogeneous distribution of activity. In addition, exposure time is important, since the dose rate is multiplied by the time in order to calculate the dose.

The effect of the size, shape and density of the source is included in the exposure factors prepared for external exposure. These may be radionuclide-specific, Sv/h per Bq/kg for a given radionuclide or relate to a mean photon energy, Sv/h per Bq/kg and MeV emitted per decay to easier combine the exposure when the material contains many radionuclides. The effect of self-shielding is also often included through simplified assumptions on how activity is distributed in the material.

Dermal exposure

Many radionuclides emit β-radiation. This type of radiation has short reach in air, but if dust containing β-radiating radionuclides congregate on the skin it may give rise to dermal exposure. The effective dose is dependent on

- how much dust there is on the skin,
- radioactivity in the dust,
- how large a skin surface is covered with dust,
- a radionuclide-specific skin dose factor.

Internal exposure

Radionuclides can enter the body through ingestion of food or drinking water that have been contaminated and by inadvertent ingestion of particles and soil. Inhalation of radioactive gases, aerosols and small particles results in radionuclides getting into the lungs. The impact of different radionuclides in the body depends on

- type of radiation (α, β, γ),
- radiation energy,
- radio-sensitivity of the exposed body part,
- biochemistry of the element.

The biochemistry is important since it governs how the element passes through the body and the time spent in different body parts. The exposed individual's age also plays a role, since the sensitivity to radiation declines with increasing age. With respect to this, radionuclide-specific dose coefficients (committed effective dose) for ingestion and inhalation have been prepared, expressed in Sv/Bq for different age groups (ICRP 2012). There are separate dose coefficients for ingestion through the mouth and inhalation. For most radionuclides, several values are given for the dose coefficients depending on how quickly different chemical forms of a radionuclide are metabolised in the body.

11.3.2 Dispersion of radionuclides

For the scenarios where impact on the environment is included, a calculation must be made of what concentrations can arise in water, air and different parts of the food web (accumulation of radionuclides should also be considered). The scenarios used for clearance usually includes

- dispersion with water,
- dispersion with dust,
- dispersion in the food web.

Figure 11-3 shows examples of dispersion and exposure pathways that can be included for the case of a landfill containing radioactive material.

Dispersion with water

Radionuclides in soil or disposed materials can be disseminated when water passes through the material and radionuclides are leached out. Leaching of radioactive substances depends on properties of both the material and the radionuclide (see further Section 11.5.4). Released radionuclides are transported down to the groundwater and can thereafter be transported further to a water recipient, for example a well, a river or a lake. The transport in groundwater can occur with very different rates and depends on permeability, water flow, dispersion due to the fact that transport rates differ between different flow paths in the groundwater zone. Furthermore, the transport rate is highly affected by retention (sorption) of radionuclides on the solid material in the groundwater zone.

Radioactive decay is of great importance for radionuclides with a half-life shorter than the transport time in the groundwater zone. Special consideration must be given to nuclides in decay chains, because they are transformed at decay into new substances with other transport properties and half-lives, which under certain circumstances may lead to an increased concentration of daughter nuclides.

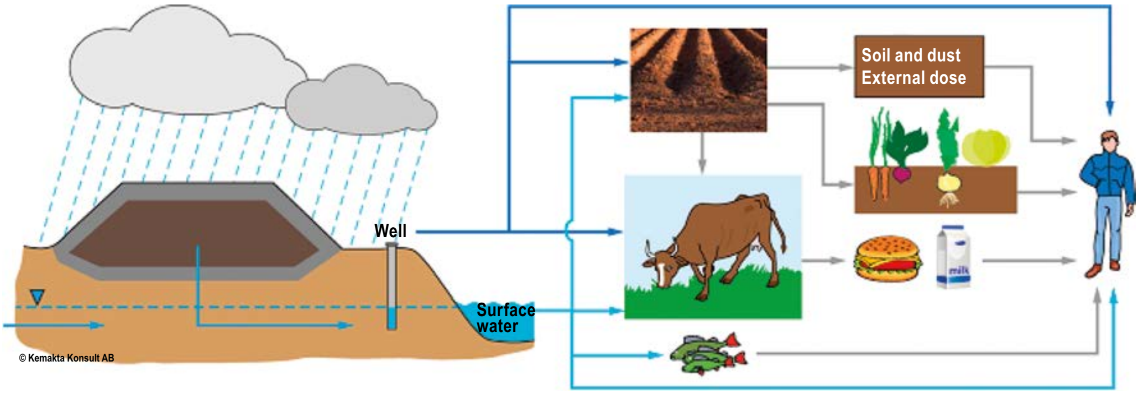

Figure 11-3. Examples of dispersion and exposure pathways from a landfill (courtesy of Kemakta Konsult AB).

The transport of radionuclides to a water recipient is time-dependent and can be described with an advection-dispersion equation that considers the immobilisation of different radionuclides, decay as well as in-growth in the case of decay chains. The equation uses parameters that describe groundwater zone properties: density, porosity, dispersion coefficient, distance along the transport path to the water recipient and water velocity. Immobilisation of radionuclides to the solid material is often described by assuming a local equilibrium. Discipline-specific K_d values (K_d = concentration in the solid material/concentration in the water) are used for this.

Both leaching and decay leads to reduced activity in the source with time. However, in-growth of progeny could lead to that the activity for certain nuclides increases with time. Time-dependent calculations for the source needs to take this into account.

Dispersion with dust

Contaminated dust can spread in the atmosphere and give rise to dose in the environment. By mixing in the atmosphere, the concentration of dust decreases with the distance from the source. Site-specific meteorological parameters can be used to calculate the dilution, but most often estimated general dilution factors are used. In some scenarios presented in IAEA (IAEA 2005), 1 % of the dust in the air close to a landfill or facility was assumed to consist of contaminated material.

Dispersion in the food web

The radionuclides in a water recipient can cause exposure of individuals that use the water for drinking, for livestock or to irrigate soil for food production. Transport pathways and transfer in the food web to humans are illustrated in Figure 11-3. If radionuclides are transported to a lake or other surface water recipient, consumption of fish may also lead to exposure of humans. Dispersion in the food web can be calculated by means of general transfer factors. A more detailed ecosystem model is usually not necessary due to the large uncertainties associated with future scenarios.

11.4 Scenarios

When clearance levels are derived, it must be ensured that the cleared material does not pose more than a trivial risk for humans, either now or in the future. General clearance levels have been produced through analysis of scenarios, with scenarios that describe different exposure situations and contain a number of conditions including behaviour and habits of the most exposed individuals. These scenarios can apply to for example work sites, accommodation, agriculture or recreational areas and contain a number of simplified exposure pathways. Their goal is to not underestimate doses that could occur in a real case.

The pessimistic assumptions on conditions made in these scenarios leads to restrictive clearance levels. Furthermore, there are many different conceivable scenarios where exposure of humans can arise and general clearance levels are governed by the scenario that gives the highest dose. Since conditional clearance applies for a given site and a given management, it is possible to limit the exposure scenarios that are relevant. Furthermore, there is often site-specific information available that can be used in the dose calculations. This may permit clearance of materials with higher activity concentrations without increasing the risk.

There are scenarios that describe exposure as a result of releases of radionuclides from nuclear facilities during normal operation. Studsvik EcoSafe's project was focused on improvements within the areas: dispersion in air and water, exposure pathways and area descriptions and critical group for the nuclear power plants in Barsebäck and Oskarshamn (Studsvik 2002a, b). There are aspects in common with conditional clearance, but also things that differ. The information for the site is largely similar, although the scenarios for normal operation mainly concern the present, and for conditional clearance the future needs to be considered to a greater extent. The release from a nuclear facility during normal operation occurs to air and a surface water recipient, while the source at conditional clearance is contaminated solid material. Therefore, both the critical group and exposure pathways will differ.

This section describes the Swedish Environmental Protection Agency's model for guideline values for contaminated land and internationally available scenarios that provide a good starting point for the choice of site- and condition-specific scenarios. Furthermore, the way of thinking behind the selection of scenarios is described and how to ensure that the selected scenarios fulfil their purpose.

11.4.1 The Swedish Environmental Protection Agency's model for guideline values for contaminated land

The Swedish Environmental Protection Agency's model for guideline values for contaminated land (Naturvårdsverket 2009), which is also a point of departure for SSM, uses two scenarios that are dependent on land use, sensitive land use including accommodation, day-care, schools, playground, and less sensitive land use including commercial areas, industries, roads or railways. For sensitive land use, there are 6 different exposure pathways that take into account direct exposure to contaminated soil through ingestion via the mouth, dermal exposure and inhalation of dust, as well as indirect exposure via inhalation of vapours and consumption of plants and groundwater that are contaminated. For less sensitive land use, only 4 of the exposure pathways are used: ingestion via the mouth, dermal exposure, inhalation of dust and vapours. For both scenarios, it is assumed that all relevant exposure pathways occur simultaneously and that guideline values are calculated from the total exposure.

11.4.2 Internationally available scenarios

There is an established methodology for calculating the dose to a critical, or most exposed, group for different exposure pathways and these have been combined in many different scenarios in various studies. There are descriptions of scenarios that are used in the derivation of general clearance levels (e.g. EC 2000b, IAEA 2005), clearance levels for buildings and building materials (EC 1999, 2000a) and clearance of decommissioning waste and land from decommissioning of nuclear facilities (NRC 1992, 1998). The permissible maximum dose to the critical group is higher in the USA, 250 µSv/year (at the state level, however, lower limits may occur), than in Europe, the order of magnitude 10 µSv/year (EU 2013). Doses due to radon inhalation are usually considered separately, for example by controlling that concentration limits for radon in air are not exceeded.

The European Basic Safety Standards (EU 2013) applies general clearance levels that are derived by the IAEA (IAEA 2005). The IAEA's report is therefore a particularly important international *guideline*. The study used eight probable scenarios, which are presented in Table 11-1 and their exposure pathways are summarised in Table 11-2.

The dose limits applied were about 10 µSv/year (the trivial dose level for nuclear facilities) under realistic conditions. Less probable conditions were also considered and compared with lower requirements, 1 mSv/year. The scenario "RH – Construction materials in residential buildings" can be used as an example to describe how a general scenario with external exposure can be designed. The individual is assumed to be in the home 4 500 (realistic) or 8 700 (low probability) hours per year and the home is a 3 × 4 × 2.5 m room. The construction material is assumed to have a density of 1 500 kg/m^3, a thickness of 20 cm and the construction material in the roof and two walls is assumed to consist to 10 % of the radioactive material.

In a scenario with exposure pathways due to dispersion through water to evaluate general clearance levels wasn't chosen, because it was considered difficult to define a general case without being too pessimistic (EC 2000b). These exposure pathways should, however, be included in scenarios for conditional clearance.

In the international documents, there are generally more examples of scenarios for clearance of material and buildings than for clearance of land, but many of these scenarios are nevertheless relevant for land.

11.4.3 Selection of scenarios

Scenarios for conditional clearance need to be considered from case to case and are expected to take into account the possible exposure of the public and workers under the assumption that specified conditions have been fulfilled. There are many issues to consider when scenarios are selected and defined and Table 11-3 presents a compilation of possible questions.

Table 11-1. Exposure scenarios considered and relevant pathways (IEAEA 2005).

Scenario	Description	Exposed individual	Relevant exposure pathway
WL	Worker on landfill or in other facility (other than foundry)	Worker	External exposure on landfill
			Inhalation on landfill
			Direct ingestion of contaminated material
WF	Worker in foundry	Worker	External exposure in foundry from equipment or scrap pile
			Inhalation in foundry
			Direct ingestion of contaminated material
WO	Other worker (e.g. truck driver)	Worker	External exposure from equipment or the load on the truck
RL-C	Resident near landfill or other facility	Child (1–2 a)	Inhalation near landfill or other facility
			Ingestion of contaminated foodstuffs grown on contaminated land
RL-A		Adult (> 17 a)	Inhalation near landfill or other facility
			Ingestion of contaminated foodstuffs grown on contaminated land
RF	Resident near foundry	Child (1–2 a)	Inhalation near foundry
RH	Resident in house constructed of contaminated material	Adult (> 17 a)	External exposure in house
RP	Resident near public place constructed with contaminated material	Child (1–2 a)	External exposure
			Inhalation of contaminated dust
			Direct ingestion of contaminated material
RW-C	Resident using water from private well or consuming fish from contaminated river	Child (1–2 a)	Ingestion of contaminated drinking water, fish and other foodstuffs
RW-A		Adult (> 17 a)	

Table 11-2. Exposure pathways applied in IAEA (2005).

Scenario	External exposure	Inhalation of dust	Ingestion of soil/dust	Drinking water	Ingestion of cultivated food	Ingestion of fish
WL – Worker on landfill or in other facility (other than foundry)	X	X	X			
WF – Worker in foundry	X	X	X			
WO – Other worker (e.g. truck driver)	X					
RL – Resident near landfill or other facility		X			X	
RF – Resident near foundry		X				
RH – Resident in house constructed of contaminated material	X					
RP – Resident near public place constructed with contaminated material	X	X	X			
RW – Resident using water from private well or consuming fish from contaminated river				X	X	X

Table 11-3. Types of questions to consider when selecting scenarios for conditional clearance.

What is the future use of the material/land?
How will people spend time in the area? Which activities may occur?
How long will people stay in the area at most? How can different activities lead to contact with radioactive material?
What values for exposure parameters (times, consumption of home-grown plants, animals) are realistic?
Will the land use change?
What alternative uses of the land are conceivable? Could they lead to higher doses? What is the probability of these uses?
Will material be transported from the site for other use? Is it likely that the use leads to a higher dose?
What age group will be most exposed?
Which scenario could lead to the very highest dose? Is this scenario at all realistic?
What would a scenario with low probability and that gives rise to high dose, but that is not unreasonable, look like?

A good start is to consider scenarios for general clearance in international documents (e.g. EC 1999, 2000b, IAEA 2005, NRC 1992, 1998, 2006, see also Section 11.4.2). These scenarios have been produced by technical expert groups and thereby provide good background information on an appropriate, although general, choice and definition of scenarios and support for reasonable assumptions. When it comes to conditional clearance, there is additional information (or opportunity to gather information) on a given site and/or specific clearance conditions that should also be included in the derivation of scenarios. In some cases, the general clearance scenarios can be adapted to the conditions, the situation and the probable future land use. In other cases, other exposure pathways and scenarios may be more relevant. Scenarios should be selected for analysis of possible exposure pathways both directly after clearance and in the future, on-site and after dispersion of material or radionuclides (Section 11.5.4). Scenarios can include for example reuse, recycling or deposition, depending on the licencing conditions. The selection of scenarios often requires some insight into future changes in land use and how they can affect exposure pathways.

When several alternative, but nevertheless probable, scenarios have been identified, however, not all of them need to be studied with detailed dose calculations but only those that are the most restrictive (result in the highest dose). The assessment of which scenarios are restrictive can be made based on previous experience and scoping calculations. What will be the most restrictive scenarios depends on the dose-related activities that may occur on the site in the different alternative scenarios, and to what extent people are engaged in these activities. Some exposure pathways are strongly time-dependent (external dose and internal dose due to inhalation of dust, ingestion of soil) and other depend on consumption habits (for example internal dose from consumption of contaminated vegetables). Dilution, depth distribution and coverage of the material may also vary between different scenarios and thereby affect the dose.

Agriculture or self-sufficiency in a contaminated area is often most restrictive due to the long exposure times, food production and the occurrence of wells some distance from the contaminated material. The NRC (NRC 2006) notes that an agricultural scenario is restrictive compared with an accommodation scenario, but in Swedish conditions these two scenarios are more similar due to greater potential for self-sufficiency. Thus, the scenario that suits the site in question and the conditions must be found.

Simplifications of dose calculations in scenarios also need to be justified due to the limited exposure pathways. For example, in (EC 2000b) it is judged that the dose from ingestion of soil is higher than the dose from vegetables and therefore did not consider the dose from vegetables. In scenarios with dispersion of water to an area some distance from the original material, water consumption is often the main exposure pathway since it is most direct, but biological accumulation of some isotopes can also lead to high exposure from, for example, ingestion of fish.

Age plays a role for both habits and sensitivity to radiation, and should be considered in the choice of critical group in scenarios. There are regional differences in habits (see Section 11.5.5), in the USA, for example, adults have the highest consumption of all food except milk, and therefore they are usually most exposed in consumption scenarios (NRC 2006). Data for Sweden shows that teenagers eat the most (Karlsson and Aquilonius 2001), which combined with their lower body weight and higher radiation sensitivity compared with adults means that they are often most exposed in consumption scenarios.

11.4.4 Ensuring selected scenarios

The selected scenarios need to provide a complete picture of restrictive, representative dispersion patterns and exposure pathways. According to experience from previous cases, SSM wants to see the reasons for selected scenarios, for example that they are based on both published examples and site-specific information. Agreement regarding both scenarios and applied values (see Section 11.5) with previous studies will make it easier for SSM to assess the results, whereas site-specific information and considerations show a good understanding of the situation and how it is likely to develop. Information from the municipality, the county administrative board and the state concerning their plans and future visions for the area should be included in order to ensure the confidence in selected future scenarios.

11.5 Data needs for dispersion and dose calculations

Dispersion and dose calculations require suitable data to give reliable results, and the need for data could be large, as shown in Table 11-4. In all scenarios, data should be chosen with reasonable caution and adapted to the selected scenarios, the site and land use. Characterisation of materials and site-specific conditions are often needed in order to conduct realistic dispersion calculations and it may also reduce the pessimism in other dose calculation parameters. This section discusses where data can be found, how they are measured or studied as well as handling of uncertainties in the data.

Table 11-4. Data needs for dispersion and dose calculations.

Type of data	Data need
Information on the material and radionuclides	**Basic data** Material composition, nuclide-specific activity, weight of waste, etc. Gamma energy of the specific radionuclide and dose factors for ingestion and inhalation.
	Scenario-affected properties Dilution factors and depth distribution of the cleared material. The material's shielding capacity in its cleared form. Dust formation properties.
	Leaching properties Leaching of radionuclides.
External exposure	Exposure times. Exposure geometry and shielding.
Direct internal exposure	Exposure times. Dust concentrations and respiratory rate. Orally ingested quantity.
Dispersion of radionuclides	Meteorological data (precipitation, evapotranspiration[1], runoff). Data describing transport pathways for water. Data describing the retardation of radionuclide transport (K_d values). Dilution in wells or surface water (lakes and rivers).
Dispersion in the food web	Amount of water for irrigation of own cultivation or agriculture. Consumption of water. Transfer factors for radionuclides from water and soil to food according to Figure 12-3. Consumption of different types of food (crops and animal products). Transfer factors for radionuclides from water to fish. Consumption of fish.

[1] Evapotranspiration is the sum of evaporation and plant transpiration.

11.5.1 Information on the material and radionuclides

Basic data

Characterisation of material composition, nuclide-specific activity concentrations, waste weight etc. is done in connection with clearance, see Chapter 4 and 7. Basic data concerning the radionuclide's gamma energy and dose factors (see Section 11.3.1) are available in reports. For example, the IAEA publishes dose factors in their *Basic Safety Standard*s (latest edition IAEA 2014a).

Scenario-affected properties

Material properties can be greatly affected due to management as a result of the clearance process or assumptions in the scenario. An example is admixture of lime that may be done to increase the pH, which leads to reduced leaching of many substances. Mixing or dilution with other materials affect the concentration of radionuclides and the material's physical properties can also be affected. This entails that a dilution factor must be estimated and that attention is needed in the choice of other parameters regarding material properties. Depth distribution of the radioactive material in the ground or a landfill also affects all exposure pathways via physical barriers for the radioactive material, shielding of radiation or proximity to the root zone and the groundwater zone. General information is also needed regarding the material's shielding capacity, since self-absorption of radiation decreases exposure.

With respect to dust, the material's ability to form dust and the probable contribution to the total dust concentration, either in a certain area or at certain work operations, needs to be assessed. Here it is also important to determine how radionuclide concentrations can vary between the actual material and the dust, for example when the bulk and surface concentrations are not equal, or when several materials contribute to the total dust concentration. The concentration of radionuclides can also vary with particle size (IAEA 2005).

Leaching properties

For scenarios that include dispersion of radionuclides with water, it is necessary to have data describing the material's tendency to release radionuclides in contact with water, which is usually called leachability. Low leachability entails that the radionuclides are tightly bound to the waste material and that the transfer of radionuclides to the water is therefore limited. Since leachability varies with both the substance and the chemical conditions, leaching tests often need to be carried out. Leachability is usually measured in sieved or crushed material (< 4 mm) in a two stage batch test according to the standard EN 12457-3 (SIS 2003) (Figure 114).

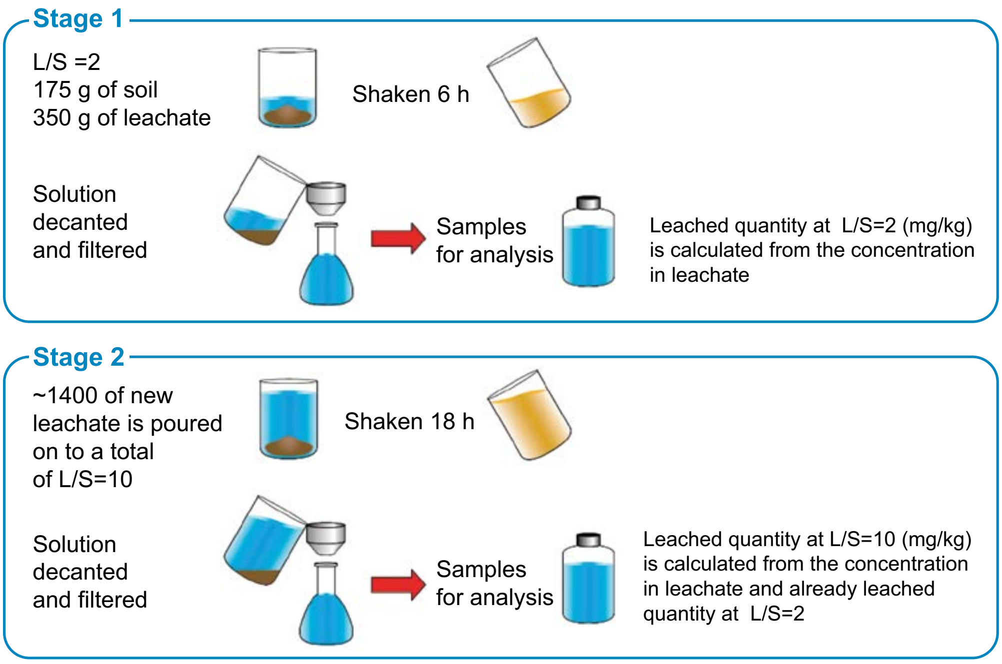

Figure 11-4. *Description of two stage leaching (L/S = 2 and 10).*

It is important to assess which analysis limits may be needed to detect the leached radionuclides in the material. In most cases it is in the order of a few percent of the content in the solid material that leaches out in a leaching test. Different types of analysis methods can be used, spectrometric, chemical and isotope analyses. For difficult-to-measure radionuclides, it is sometimes possible to use results for other isotopes of the element or for chemically similar elements.

Waste in a landfill can be a mixture of various materials and substances and has very heterogeneous chemical and physical properties. Different waste types can therefore be expected to have different leaching properties. Leaching of radionuclides from the radioactive waste is determined, not only by the properties of the waste, but also by the environment. It is very important that the samples analysed are representative for both the material and the mixture that will occur at the landfill.

The results from two stage leaching can often be represented by the assumption of exponential release of radionuclides from the material. This means that the concentration in the leachate declines exponentially with water volume/time according to Figure 11-5. The shape of the curve is determined by the kappa parameter. A high value for kappa implies fast leaching, while a low kappa value entails a more constant leaching. All activity in a material is not leachable and the results from leaching tests also make it possible to perform an estimate of how large a fraction of the radionuclide activity that can be leached out. Attention must also be given to how the waste properties can change with time, as a change of e.g. the material's ability for pH buffering can affect the leachability. Batch tests can therefore be supplemented with pH-static leaching tests[5], in order to obtain information on how the material acts at different pH values and the material's buffering capacity.

More information about concentration development can be gained from percolation tests (column tests) according to the standard SS-CEN/TS 14405 (SIS 2004). These tests measure the leachate that flows through a column packed with a dry granular material at different L/S ratios, often L/S = 0.1; 2 and 10. This test takes longer, typically a few weeks and is considerably more expensive than batch tests.

11.5.2 External exposure

Exposure time, geometry and shielding are defined in each scenario and the international documents that support the selection of scenarios (Section 11.4.3) can also provide support for the selection of suitable data.

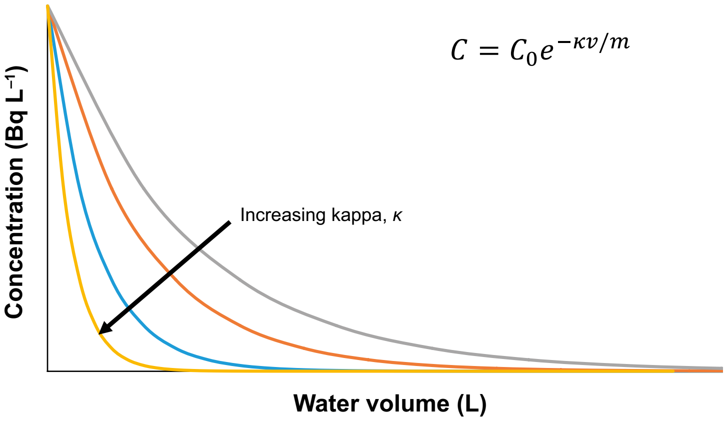

Figure 11-5. *Leachate concentration as a function of water volume that has leached the material for different exponentially declining leaching rates.*

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[5] In pH-static leaching tests, the material is leached at a pH that is held constant through the addition of a base or acid. The analysis is often conducted with pH 4, 6, 8 and 10 and with the material's natural pH.

11.5.3 Internal exposure

Calculation of the internal dose is based on inhalation of dust and ingestion of dust, soil or particles. Data are therefore needed on dust content in the air and respiratory rates as well as an orally ingested quantity of dust, soil or particles. The dust content varies greatly with the environment, from everyday situations with low dust content to dusty work environments such as crushing during demolition of buildings. According to Arbetsmiljöverket (the Swedish Work Environment Authority) (AFS 2011:18), the maximum permissible respirable dust content in a work environment is 5 mg/ m^3, although this is often exceeded for demolition work (Karlsson and Christensson 2008). The effect of using a mask or filters in work machines vary greatly (Fjällström et al. 2009) and based on reported measurements, a general reduction factor of 20 can be chosen with the use of a mask. The IAEA used a dust content of 0.5 mg/m^3 in a work environment and 0.1 mg/m^3 for public places, and a respiratory rate for an adult of 1.2 m^3/h (IAEA 2005).

11.5.4 Dispersion of radionuclides

To calculate the dispersion of radionuclides and the doses that arise from using water from a contaminated water source, data are needed for each step of the analysis (see Section 11.3.2).

The first step is to calculate leaching of radionuclides, which is based on leachability data, as described in Section 11.5.1. Leaching is also dependent on the water flow through the contaminated material and therefore, meteorological data are needed for choosing representative parameter values for precipitation, evapotranspiration and runoff in the contaminated area. Data are available from public data sources, for example SMHI, authorities and site-specific studies. If conditional clearance applies for deposition, there might be information on the landfill infiltration, particularly if it is an existing landfill with a classification.

When the radionuclides have begun to leach, the dispersion is dependent on the water's transport pathway. If there are no hydrogeological data for the area, site-specific investigations should be carried out, including

- site-specific geology (soil types, bedrock, permeability and porosity),
- hydrology (location relative to contaminated land/landfill; depth and extent of the groundwater zone, water flow),
- nearby water recipients and probable sites for a well need to be identified.

The hydrogeological conditions also determine the dilution in the well or surface water (lakes and rivers) to which the radionuclides are transported. The location of a probable future or existing well must take into account that the water should be potable, which makes it necessary to also consider how the cleared material may affect water quality with respect to other aspects (pH, solutes, heavy metals, etc).

With knowledge of the groundwater zone's solid material and preferably also the water chemistry, it is possible to choose representative K_d values that describe the retardation of transport of individual solutes and radionuclides. K_d values can be adapted to site-specific conditions, for example pH, geochemical redox conditions or high concentrations of complexing agents in the water. The more knowledge of the groundwater zone's solid material and the water chemistry, the better material for selection of representative K_d values. In the absence of site-specific data general, pessimistic K_d values can be used. It is also possible to measure site-specific K_d values, but it requires extensive investigations and analyses.

11.5.5 Dispersion in the food web

The dispersion in the food web starts with either radioactive land (on the original site or in a landfill) or radioactive water in a well or surface water recipient (after dispersion with water). In the first case, the dilution with other materials governs radionuclide concentrations in the soil and in the other case, the irrigation rate and irrigation time for cultivation and immobilisation of radionuclides on the ground. Irrigation and immobilisation of radionuclides also leads to external exposure and internal exposure via ingestion and inhalation of radioactive soil particles. Parameter values for these data can be chosen using publicly available information.

Water consumption must also be defined for humans and animals in dispersion scenarios (Figure 11-3) and for the public the individual's water consumption is often an important exposure pathway. Transfer factors from soil to plants vary depending on the soil type, and transfer factors from different soil types to plants, plants to animal products and fresh water to fish have been evaluated (IAEA 2010). Eating habits should be selected from publicly available information, so that they are representative for the site, since they vary regionally. For example, in (IAEA 2005) German consumer habits, where adults consume 1.7 kg of fish per year are used in comparison with data for Swedish consumer habits of 27 kg of fish per year, which are used in the calculation of dose consequences for removal of waste containing uranium from the sorting plant in Ranstad (Kemakta 2012). The probability that home-grown food is the only food source also depends on the site and is higher for individuals that live in rural areas than for individuals in urban areas. In the scenarios in (IAEA 2005) it is assumed that 25 % of the food comes from the contaminated area , compared with an assumption of100 % in a corresponding Swedish study (Kemakta 2012).

11.5.6 Handling of uncertainties of input parameters

All parameters used in a dose calculations are subject to uncertainties. Some uncertainties are easier to distinguish and assess than others, but it is important that the uncertainties are described and handled in a consistent and structured manner.

Uncertainties associated with the radionuclide concentrations in the material and material quantities are assessed in conjunction with the characterisation (see Chapter 4 and 7). The effect of these uncertainties can then be studied in the dispersion and dose calculations.

When calculating dispersion and dose, there are other uncertainties built in through the choice of parameters that are realistic but somewhat pessimistic, for example those controlled by possible activities, dilution with other materials, behaviour and eating habits. The importance of known or expected variations in parameter values can be explored by calculating variation cases. In many cases, the models used are linear so it is relatively straightforward to predict what a change in a parameter value entails. Certain parts, such as models for dispersion in the groundwater, may provide a nonlinear response, and it is therefore not easy to predict what a variation of a parameter entails.

Sometimes it is difficult to determine a reasonable limitation of a parameter value. One way to handle it is to define scenarios that are restrictive, but with much lower probability than the base case. Since there is a lower probability for these, they can therefore be considered to have lower requirements with regard to the calculated dose. The requirements according to the IAEA (IAEA 2005) for "realistic" scenarios are a maximum dose of 10 µSv/year (trivial risk) and for scenarios with "low probability" a maximum dose of 1000 µSv/year (maximum dose to the public). This is, however, not implemented in the Swedish regulations SSMFS 2011:2 (SSM 2011).

Another way to handle data uncertainties is to perform probabilistic calculations (e.g. Monte Carlo simulations). In the USA for example, probabilistic uncertainty analyses are made where the "maximum mean dose" is used to show compliance with the regulations (NRC 2006). However, probabilistic calculations require extensive knowledge concerning parameters and furthermore, the uncertainties in choice and design of scenarios are likely to be more important. Thus a deterministic assessment is primarily recommended.

12 Cost model

12.1 Boundaries and conditions

Calculated costs for decommissioning of the Swedish nuclear power plants are reported in the most recently completed decommissioning studies (SKB 2013a, b, c, Griffiths et al. 2008). Based on these studies and the clearance process in Section 2.2, a cost model for clearance is proposed in this chapter.

As a basis for assessing the costs for clearance of material, compared with other disposal options, reference is made to the Clearance Manual (SKB 2011). This chapter will only consider buildings and land, since final disposal of these within the Swedish radioactive waste management system is not assumed to be a realistic alternative. This chapter therefore does not intend to create a model for comparison of different disposal options.

12.2 Model

In order to create a cost model that sheds light on the factors affecting the cost of the clearance process, constituent cost elements have been identified on the basis of reference cases depending on risk categorisation. The result is a *bottom-up* model, similar to how cost estimates are prepared for dismantling and demolition in the decommissioning studies for the nuclear power plants (SKB 2013a, b, c, Griffiths et al. 2008).

By starting from the reported clearance process in Figure 2-2 and the recommendations in this report, four reference cases can be identified depending on the risk categorisation in Figure 12-1.

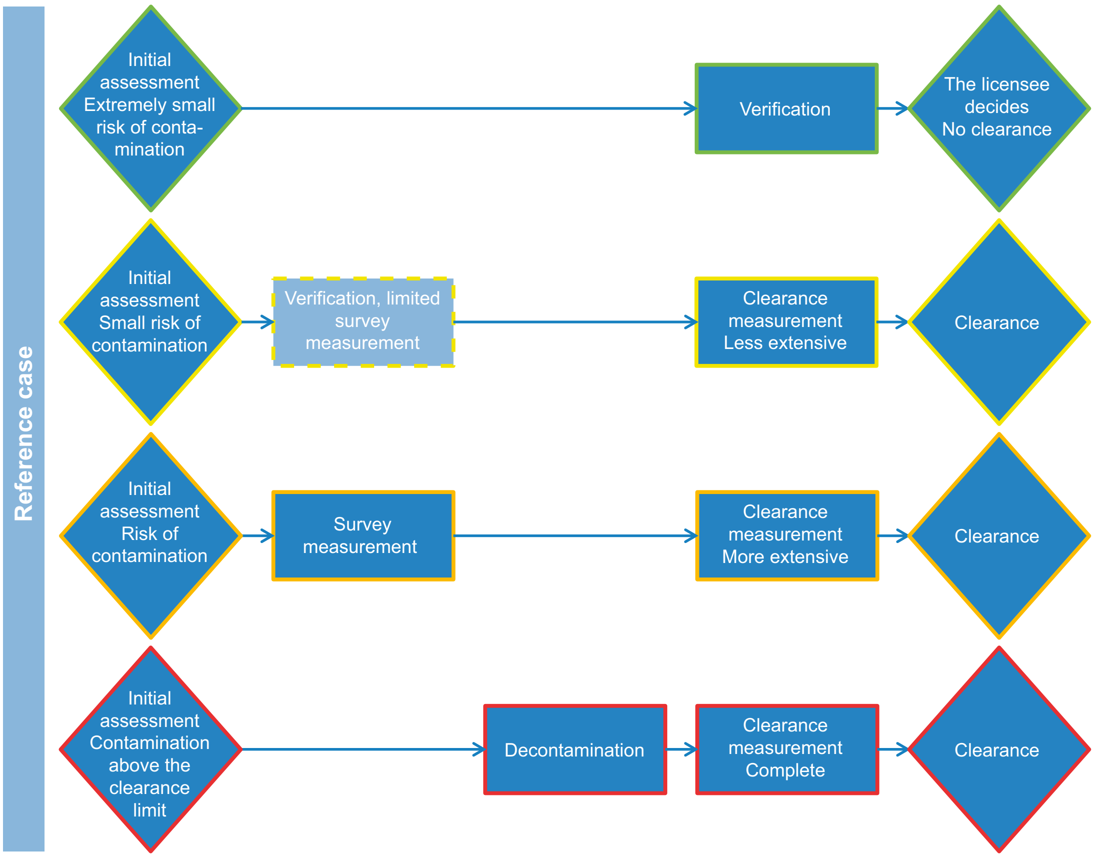


***Figure 12-1.** Four reference cases for handling objects depending on risk categorisation.*

Each element included in the reference cases according to Figure 12-1 is a constituent cost element in the cost model for clearance. Each cost element consists of activities which are presented in Figure 2-2. By identifying these activities, cost elements are built up depending on the risk category.

The necessary activities for each cost element in turn consists of various costs. These costs consist of the time required for work (competencies/resources) and the costs for equipment and consumables. Based on experience and previously known data for these costs and times, a cost is developed for a cost element depending on the size, nature and risk categorisation of the object.

Some derived unit costs/key ratios for each operation are presented in the decommissioning studies (SKB 2013a, b, c, Griffiths et al. 2008). They can for example be costs and time for different types of decontamination and clearance measurements. These unit costs may need to be developed as more experience of clearance is built up in Sweden, with respect to how the extent of the work varies depending on risk categorisation and application of relevant requirements. Type of competence/resources, equipment and consumables can be similar regardless of cost elements and reference cases. By applying different weighting factors depending on the reference case, different costs and times will be obtained depending on the extent. For example, no difference can be seen in the execution of a clearance measurement for the risk category *risk of contamination* compared with a clearance measurement for the risk category *contamination above the clearance limit*, but in the latter case it may be a question of a complete measurement covering the entire object, which gives a higher weighting factor. To exemplify differences in measurement efforts depending on risk categorisation as well as differences in survey or clearance measurement, the extent of survey and clearance measurement for a hypothetical facility is presented in Appendix D.

Each cost estimate for a reference case must also be timed and built up of activities that can be produced by means of a Gantt chart, which is a type of flowchart used in project management for describing different phases. This can then be included in the entire decommissioning project's project plan and thereafter, analyses can be made of the extent to which clearance affects the critical path and thereby which time-dependent costs in the form of project management, energy consumption, etc. are affected.

12.2.1 Examples of cost estimation

In order to describe how costs can be estimated and can vary depending on risk category, a number of examples are provided here. They are based on the risk categorisation in Figure 12-1 for an assumed room with the dimensions width = 10 m, length = 20 m and roof height = 5 m and with the following conditions (SKB 2013a, b):

- Complete clearance measurement is performed with 100 % measurement of β/γ-emitting nuclides and random samples for α-emitting nuclides. The time needed is 20 min/m^2.
- More extensive clearance measurement is performed with 50 % measurement of β/γ-emitting nuclides and random samples for α-emitting nuclides. The time needed is 15 min/m^2.
- Less extensive clearance measurement is performed with measurement of β/γ-emitting nuclides through random samples, which is equivalent to about 20 % of the surface being measured. The time needed is 10 min/m^2.

The time needed for each object includes clearance measurement and documentation of results.

Example 1

Roof area	200 m^2	Small risk of contamination	Less extensive clearance measurement	10 min/m^2	33 h
Wall area	300 m^2	Risk of contamination	More extensive clearance measurement	15 min/m^2	75 h
Floor area	200 m^2	Contamination above the clearance limit	Complete clearance measurement	20 min/m^2	67 h
				Total	**175 h**

Example 2

Roof area	200 m^2	Small risk of contamination	Less extensive clearance measurement	10 min/m^2	33 h
Wall area	300 m^2	Small risk of contamination	Less extensive clearance measurement	10 min/m^2	50 h
Floor area	200 m^2	Risk of contamination	More extensive clearance measurement	15 min/m^2	50 h
				Total	**133 h**

Example 3

Roof area	200 m^2	Small risk of contamination	Less extensive clearance measurement	10 min/m^2	33 h
Wall area	300 m^2	Small risk of contamination	Less extensive clearance measurement	10 min/m^2	50 h
Floor area	200 m^2	Small risk of contamination	Less extensive clearance measurement	10 min/m^2	33 h
				Total	**117 h**

The examples above show about ±25 % difference in the time needed for requisite clearance measurement in an assumed room depending on the contamination level assumed for the different surfaces and the specific time assumed for measurement of these surfaces.

12.3 Preparation of cost estimates

During a clearance process, cost estimates need to be reviewed and revised based on the increased information and understanding obtained. Estimates will also be transformed to budget costs when work extent and quotes from contractors are prepared. This section describes a recommendation concerning in what stages in the clearance process the estimated costs should be updated.

Through the information gathered during the *initial assessment* when a plan is prepared for the continued work, the cost estimate should be adapted to this and compared with previous estimates.

Before *survey measurements* are carried out the planning of their extent is important. Depending on how the work is planned and procured, the cost estimate can be supplemented with information from actual quotes from suppliers. As work progresses and the cost outcome is compared with the remaining estimate, a more precise cost picture is obtained.

After the survey work, the extent of decontamination work can be established which is a part of the *preparations prior to clearance measurement*. When this work is procured and established, the cost estimate is revised. When the decontamination work is completed, the estimated part of the costs will consist of clearance measurements, while the rest is the outcome.

The work has then come so far that it is time for *clearance measurement.* In this planning it is important that work is procured and cost estimates revised.

When the work with *clearance measurement* is defined and procured, the cost estimate can be revised one last time. During this phase, the main part of the measurements in the clearance process are conducted and the consumption of resources is high, which is reflected in Appendix D where the extent of measurements is exemplified. If different parts of an object undergo clearance measurement at different times, the results of the first clearance measurement can show whether the extent of measurements was sufficient. If necessary, the extent of measurements can be revised for the remaining parts of the object and then the cost estimate can also be revised.

The remaining costs consist of preparing the application for *clearance*, for which the clearance report is a basis. After this phase, the decommissioning project can evaluate the final outcome for the cost of clearance which can be incorporated into the cost model in the form of new unit costs and weighting factors.

12.4 Evaluation of costs

ALARA and BAT should be applied as general principles in the clearance process for example when selecting measurement and decontamination methods. However, these principles should also be compared with the cost for alternative methods. Costs can for example be referred to in order to justify

- conditional clearance,
- greater extent of decontamination,
- larger quantity of radioactive waste.

12.5 Uncertainties

Estimated costs for a reference case are based on given conditions and that the management is ideal and takes place according to plan. Depending on a number of different factors, the conditions may change and thereby the cost estimate will also change both in the form of increased or reduced costs. For example, an object may be reclassified to another risk category after the survey or clearance measurement, which directly affects the costs for clearing the object.

In the work with uncertainty analysis and the assessment of which reference case should be used for an object, it can be justified to conduct a cost calculation for several reference cases (alternative risk categories), to form an idea of the risks and opportunities connected with the outcome of the risk categorisation.

During the execution of a clearance and decommissioning project, uncertainties are handled continuously by reducing risks and carrying out opportunities. As the project progresses, the cost estimate consists of both the real outcomes and estimated costs, which means that the uncertainty declines gradually.

12.6 Cost drivers

Cost drivers in this context refers to factors that affect the costs. The following is a number of examples of cost drivers linked to clearance for a nuclear facility's entire service life. This includes the phases operation, transition period and dismantling and demolition. It is important to identify cost drivers and how they affect the costs to cover uncertainties.

Work within the OECD/NEA (OECD/NEA 2010) has identified cost drivers significant in cost estimates for decommissioning and those concerning clearance are

- changed extent of the decommissioning project, i.e. increased or decreased extent, changed requirements and increased requirements on information and level of detail,
- stakeholders' influence on the final state of the site and management of waste,
- characterisation of the facility with regard to materials, activity and environmentally hazardous waste,
- storage of waste and availability of alternatives for management and removal,
- management of cleared objects.

12.6.1 Operation

During the operation of a nuclear facility, a requirement is that there is a plan for decommissioning, including management of waste and clearance, with an increasing level of detail as shutdown approaches. Furthermore, continuous cost calculations are made for decommissioning and the uncertainties should be reduced when the start of the decommissioning project approaches.

Before shutdown approaches and the decommissioning project starts in preparation for shutdown, it may be sufficient to know at a general level which the large cost drivers are.

When a decommissioning project has started and detailed planning is carried out for decommissioning some years before shutdown, cost calculations need to be specified in more detail so that investment decisions can be taken for implementation of the project. It will then be important to have a comprehensive and detailed picture of cost drivers. This is especially important in order to conduct uncertainty analyses as correct as possible and actively work to minimise project risks and carry out project opportunities.

Examples of cost driving factors during operation with respect to clearance are

- incorrect management of contaminated material in the facility, i.e. incorrect management of risk categorisation of the facility,
- how/if systematic characterisation/survey work is conducted,
- maintenance of the facility that minimises leakage,
- inadequate planning for clearance and how it affects the project when it starts,
- which final state is determined or that not final state is determined, affects extent and costs of clearance,
- quality of historical data/information such as instructions for archiving, systematic reporting of events that affect clearance,
- absence of adequate inventory/characterisation/information,
- absence of resources/competence for decommissioning and clearance,
- absence of specified requirements during normal operation with respect to decommissioning and clearance in the business management system,
- inadequate handling of risk categorisation.

12.6.2 Transition period

The decommissioning project continues during this period, which means that factors affecting the critical path for the project are important.

Examples of cost driving factors during the transition period with respect to clearance are:

- inadequate survey, which is important for verification/revision of risk categories, thereby multiple demolition activites cannot begin as quickly as possible and take place in parallel depending on what is intended to be cleared,
- the extent of measurements for the survey that affects the timetable and also the basis for making future decisions,
- extended timetable for this period, which means that information and documentation becomes obsolete and that competence and experience are lost.

12.6.3 Dismantling and demolition

During dismantling and demolition, the decommissioning project is most active and progresses with maximum workforce. Therefore, the factors that affect the total timetable become cost drivers. This period is concluded with clearance which is the formal concluding part, and entails that the decommissioning project can be considered concluded. Thereby, clearance is the most important parameter to complete the project.

Examples of cost driving factors during dismantling and demolition with respect to clearance are

- number/extent of measurement resources for clearance measurements that affect the timetable,
- lack of clarity and insufficient information for decisions on clearance, the project does not end,
- choice of measurement methods,
- if clearance occurs as material or building,
- if clearance of buildings is performed for decommissioning or for continued use,
- process flow (facility) for clearance, to make it rational and large-scale,
- choice of technology for clearance,
- regulatory requirements,
- licensing processes.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications. SKBdoc documents will be submitted upon request to document@skb.se.

AFS 2011:18. Hygieniska gränsvärden (Occupational exposure limit values). Stockholm: Arbetsmiljöverket. (In Swedish.)

Carrel F, Gmar M, Schoepff V, 2011. GAMPIX: a new generation of gamma camera. Proc. Characterization and Visualization Technologies in DD&R. Available at: https://www.iaea.org/OurWork/ST/NE/NEFW/WTS-Networks/IDN/idnfiles/Characterization&Visualization/04-New_gamma_imaging_GAMPIX.pdf [20 June 2016].

Desnoyers Y, Dubot D, 2012. Data analysis for radiological characterisation: geostatistical and statistical complementarity. Proceeding of Workshop on Radiological Characterisation for Decommissioning, Studsvik, Sweden, 17–19 April 2012.

EC, 1993. Principles and methods for establishing concentrations and quantities (exemption values) below which reporting is not required under the European directive, Radiation Protection 65, Doc XI-028/93, European Commission.

EC, 1999. Definition of clearance levels for the release of radioactively contaminated buildings and building rubble. Radiation Protection 114. European Commission.

EC, 2000a. Recommended radiological protection criteria for the clearance of buildings and building rubble from the dismantling of nuclear installations. Radiation Protection 113. European Commission.

EC, 2000b. Practical use of the concepts of exception and clearance – Part 1. Guidance on general clearance levels for practices. Radiation Protection 122. European Commission.

EPA, 2006a. Guidance on systematic planning using the data quality objective process, (EPA QA/G-4). EPA/240/B-06/001, U.S. Environmental Protection Agency, Washington, DC.

EPA, 2006b. Reference guide for radioactively contaminated surfaces. EPA-402-R-06-003, U.S. Environmental Protection Agency, Washington, DC.

EPA, 2007. Technology reference guide for radioactively contaminated media. EPA-402-R-07-004, U.S. Environmental Protection Agency, Washington, DC.

EU, 2010a. Treaty establishing the European Atomic Energy Community. European Union.

EU, 2010b. Commission recommendation of 11 October 2010 on the application of Article 37 of the Euratom Treaty (2010/635/Euratom). European Union.

EU, 2013. Council directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom European Union.

Fjällström P, Wängberg I, Christensson B, 2009. Hur effektivt skyddar andningsskydd i praktiken? IVL Rapport B1876, IVL Svenska Miljöinstitutet AB. (In Swedish.)

Gelman A, Carlin J, Stern H, Dunson D, Vehtari A, Rubin D, 2004. Bayesian data analysis. 2nd ed. Boca Raton, FL: Chapman & Hall.

Gilmore G, 2008. Practical gamma-ray spectrometry. 2nd ed. Chichester: Wiley.

Griffiths G M, Garrett T J, Cloutier W A, Adler J J, 2008. Decomissioning cost analysis for Barsebäck nuclear station. Document S33-1567-002, rev 0, TLG Services, Inc. SKBdoc 1403739 ver 1.0, Svensk Kärnbränslehantering AB.

IAEA, 2002. Record Keeping for the Decommissioning of Nuclear Facilities: Guidelines and Experience. IAEA Technical Reports Series 411, International Atomic Energy Agency.

IAEA, 2003. Derivation of activity limits for the disposal of radioactive waste in near surface disposal facilities. IAEA-TECDOC-1380, International Atomic Energy Agency.

IAEA, 2005. Derivation of activity concentration values for exclusion, exemption and clearance. IAEA Safety Reports Series 44, International Atomic Energy Agency.

IAEA, 2007. IAEA safety glossary: terminology used in nuclear safety and radiation protection. 2007 Edition. International Atomic Energy Agency.

IAEA, 2010. Handbook of parameter values for the prediction of radionuclide transfer factors in terrestrial and freshwater environments. IAEA Technical Reports Series 472, International Atomic Energy Agency.

IAEA, 2012. Monitoring for Compliance with Exemption and Clearance Level. IAEA Safety Reports Series 67, International Atomic Energy Agency.

IAEA, 2014a. Radiation protection and safety of radiation sources: International Basic Safety Standards. IAEA Safety Standards Series GSR Part 3, International Atomic Energy Agency.

IAEA, 2014b. Decommissioning of Facilities. IAEA Safety Standards Series GSR Part 6, International Atomic Energy Agency.

ICRP, 2012. Compendium of dose coefficients based on ICRP Publication 60. Oxford: Pergamon. (ICRP Publication 119; Annals of the ICRP 41 (Supplement 1)).

ISO, 2005. ISO/IEC 17025:2005: General requirements for the competence of testing and calibration laboratories. Genève: International Organization for Standardization.

ISO, 2008. ISO 9001:2008: Quality Management Systems – Requirements. Genève: International Organization for Standardization.

Karlsson A, Christensson B, 2008. Effektiva åtgärder mot damm på byggarbetsplatser: etapp 1. IVL Rapport B1794, IVL Svenska Miljöinstitutet AB. (In Swedish.)

Karlsson S, Aquilonius K, 2001. Dosomräkningsfaktorer för normaldriftsutsläpp. C. Exponeringsvägar och radioekologiska data. STUDSVIK/ES-01/35, Studsvik Eco & Safety AB. (In Swedish.)

Kemakta, 2012. Beräkning av doskonsekvens vid bortskaffning av uranhaltigt avfall från rivning av sovringsverket i Ranstad. AR 2012-35, Kemakta Konsult AB. (In Swedish.)

Lilliefors H W, 1967. On the Kolmogorov–Smirnov test for normality with mean and variance unknown. Journal of the American Statistical Association 62, 399-402.

Lundgren K, 2012. Svenska LWR – Aktivitetsinventarium vid rivning – Modellbeskrivning. Studsvik ALARA Engineering. Rapport 12-0028R, Studsvik Nuclear AB. (In Swedish.)

Naturvårdsverket, 2009. Riktvärden för förorenad mark: modellbeskrivning och vägledning. Rapport 5976, Naturvårdsverket. (In Swedish.)

Norberg T, 2012. Analys av osäkerheter i uppmätta medelaktiviteter e dyl i sovringsverket. Matematik- och statistikkonsult. (In Swedish.)

NRC, 1992. Residual radioactive contamination from decommissioning: technical basis for translating contamination levels to annual effective dose equivalent: final report. NUREG/CR-5512, Nuclear Regulatory Commission, Washington, DC.

NRC, 1998. Decision methods for dose assessment to comply with radiological criteria for license termination. NUREG-1549, Nuclear Regulatory Commission, Washington, DC.

NRC, 2000. Multi-agency radiation survey and site investigation manual Rev. 1. NUREG 1575, Nuclear Regulatory Commission, Washington, DC.

NRC, 2004. Multi-agency radiological laboratory analytical protocols manual. NUREG-1576, Nuclear Regulatory Commission, Washington, DC.

NRC, 2006. Consolidated Decommissioning Guidance: Characterization, Survey and determination of radiological criteria. NUREG-1757, Nuclear Regulatory Commission, Washington, DC.

OECD/NEA, 2010. Cost estimation for decommissioning: an international overview of cost elements, estimation practices and reporting requirements. Paris: OECD/NEA.

OECD/NEA, 2013. Radiological characterisation for decommissioning of nuclear installations. Paris: OECD/NEA.

ORISE, 2008. Survey procedures manual for the independent environmental assessment and verification program. Oak Ridge, TN: Oak Ridge Institute for Science and Education.

SDF, 2005. Clearance and radiological sentencing: principles, processes and practices for use by the nuclear industry. A nuclear industry code of practice, Issue 2. Nuclear Industry Safety Directors Forum, UK.

SFS 1977:1160. Arbetsmiljölag (Work Environment Act). (In Swedish.)

SFS 1984:3. Lag om kärnteknisk verksamhet (The Nuclear Activities Act). (In Swedish.)

SFS 1988:220. Strålskyddslag (Radiation Protection Act). (In Swedish.)

SKB, 2011. Kärntekniska industrins praxis för friklassning av material, lokaler och byggnader samt mark. Handledning. SKB R-11-15, Svensk Kärnbränslehantering AB. (In Swedish.)

SKB, 2013a. Decommissioning study of Forsmark NPP. SKB R-13-03, Svensk Kärnbränslehantering AB.

SKB, 2013b. Decommissioning study of Oskarshamn NPP. SKB R-13-04, Svensk Kärnbränslehantering AB.

SKB, 2013c. Ringhals Site Study 2013 – An assessment of the decommissioning cost for the Ringhals site. SKB R-13-05, Svensk Kärnbränslehantering AB.

SIS, 1997. SS-ISO 11932: Activity measurements of solid materials considered for recycling, re-use, or disposal as nonradioactive waste. Stockholm: Swedish Standards Institute.

SIS, 2003. SS-EN 12457-3: Characterization of waste – Leaching – Compliance test for leaching of granular waste materials and sludges – Part 3: Two stage batch test at a liquid to solid ratio of 2 l/kg and 8 l/kg for materials with high solid content and with particle size below 4 mm (without or with size reduction). Stockholm: Swedish Standards Institute.

SIS, 2004. SS-CEN/TS 14405: Characterization of waste – Leaching behaviour tests – Up-flow percolation test (under specified conditions). Stockholm: Swedish Standards Institute.

SIS, 2010. SS-ISO 11929:2010: Determination of the characteristic limits (decision threshold, detection limit and limits of the confidence interval) for measurements of ionizing radiation – Fundamentals and application (ISO 11929:2010, IDT). Stockholm: Swedish Standards Institute.

SSM, 2008. The Swedish Radiation Safety Authority's Regulations concerning safety in nuclear facilities. Stockholm: Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority). (SSMFS 2008:1)

SSM, 2011. Strålsäkerhetsmyndighetens föreskrifter och allmänna råd om friklassning av material, lokaler, byggnader och mark vid verksamhet med joniserande strålning. Stockholm: Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority). (SSMFS 2011:2) (In Swedish.)

Studsvik, 2002a. Dosomräkningsfaktorer för utsläpp till luft och vatten vid normal drift av Barsebäcksverket, STUDSVIK/ES-02/26. BKAB id nr B1013810, Studsvik Eco & Safety AB. (In Swedish.)

Studsvik, 2002b. Dosomräkningsfaktorer för utsläpp till luft och vatten vid normal drift av Oskarshamnsverket, STUDSVIK/ES-02/26, Studsvik Eco & Safety AB. (In Swedish.)

Appendix A

Definitions

A1 Definitions, terms and concepts

Determination of activity

Nuclide-specific determination of activity is made by measurement or calculation (nuclide vector) of the activity.

Activity check

Entails measurement of radioactive contamination and should first be done by checks for loose contamination with smear tests and by measurement with count rate equipment. For all materials except tools and equipment that will be used in the same way, a nuclide-specific determination of activity is also needed to verify that the clearance conditions stipulated by regulatory authorities are met.

Alpha emitters with low radiotoxicity

Natural uranium, depleted uranium, natural thorium, uranium-235 or uranium-238, thorium-232, thorium-228 and thorium-230 when they occur in ore or in physical or chemical concentrates, and alpha emitters with a half-life below ten days.

Transition period

Based on SSMFS 2008:1, Chapter 9. The initial period during decommissioning directly after final shutdown of a facility. During this period the fuel is managed and some preparations can be done for dismantling and demolition, such as decontamination of primary reactor circuits, survey work and adaptations of buildings and systems.

Decommissioning

SSMFS 2008:1, 1 chapter § 2. Measures taken by the licensee after final shutdown of a facility in order to dismantle and demolish all or parts of the facility, and to reduce the amount of radioactive elements in soil and remaining buildings to such levels that permit clearance of the facility.

BAT

Best Available Technique, using the most effective method to limit releases of radionuclides and detrimental effects on human health and the environment, without leading to unreasonable costs, (SSMFS 2008:23, § 2).

Disposal

Management of waste with methods specified in the Waste Management Ordinance SFS 2001:1063 Appendix 5, for example different types of deposition, incineration, etc.

Decontamination

Decontamination refers to measures for removal of activity from an object by physical or chemical separation.

Direct clearance

By measurement with advanced instruments log and calculate a mean value of the result to permit clearance in one step.

Operation

Refers to the main activities for which a facility is built. The period extends from construction and up to final shutdown. Thereafter follows decommissioning, which lasts until the facility is dismantled and demolished.

Self-monitoring

Inspection that is carried out in the own activities (also at external actors) and on individual responsibility.

Ex situ measurements

The measurement object is taken to another site where measurement is performed, for example when the background level at the site is too high.

Fissile material

Fissile nuclides are uranium-233, uranium-235, plutonium-239 and plutonium-241**.**

Clearance

With clearance is meant that the Radiation Protection Act (1988:220) and the Nuclear Activities Act (1984:3) are no longer applicable to materials, rooms, buildings and land that may have been contaminated with radioactive substances in practices involving ionising radiation (SSMFS 2011:2, § 2). Materials, buildings and land have been checked and their content of radionuclides are below stipulated **Clearance levels.**

Clearance limit

Refers to a limit of the value when clearance can take place. This is described as a requirement according to the sum formula for nuclides in SSMFS 2011:2.

Clearance level

Refers to nuclide-specific levels for clearance.

Industrial area

Area intended for the establishment of industries and other companies without direct contact with consumers. In an industrial area there may also be waste management, service workshops, or other activities that can not be mixed with accommodation.

In situ measurement

Measurement of an object on site.

ISOCS

In situ Object Counting System (brand). Measurement equipment for mobile gamma spectroscopy based on a HPGe detector from CANBERRA.

ISOTOPIC

Measurement equipment from ORTEC (brand), which is of the same type of system as ISOCS.

Characterisation

By investigating and analysing an object creating an idea of its constituents. For example material composition and the presence of radioactive and environmentally hazardous elements.

Survey

Status determination of an object based on the occurrence of radioactive substances.

Survey measurement

Targeted measurement that is performed during survey.

Categorisation

See **Risk categorisation**. Division of objects according to the risk of radiological contamination.

Confidence

The reliability of an experiment or measured value.

Controlled area

Based on SSMFS 2008:51, 4 kap. 3 §. An area where the annual effective dose may be above 6 mSv, or where surface contamination may exceed the current limit.

Special rules apply for a controlled area in order to protect against ionising radiation and prevent dispersion of radioactive contamination. Access to the controlled area is supervised. At the entrace to the controlled area, levels for direct radiation, surface contamination and airborne activity should be indicated.

In a clearance context, areas categorised with respect to surface contamination and/or airborne activity are of the greatest importance. A controlled area only with respect to direct radiation can be of importance in risk categorisation, since it may lead to some risk of radioactive contamination.

See also **Protected area**.

Control programme

Based on SSMFS 2011:2, 8 §. An established documentation that describe methods for and extent of the checks, who is authorised to carry out the checks as well as information on quality assurance, self-monitoring and documentation of results.

Clearance measurement

Based on SSMFS 2011:2, 8 §. Refers to the measurement that verifies the checks, according to the prepared **Control programme**, with respect to the occurrence of radioactive substances before clearance can take place.

Nuclear waste

(Taken from “The Act (1984:3) on Nuclear Activities”).

a. spent nuclear fuel that has been placed in a final repository,
b. radioactive substances that have arisen in a nuclear facility and that have not been produced or removed from the facility in order to be used for educational or research purposes or for medical, agriculture-technical or commercial purposes,
c. material or other that has belonged to a nuclear facility and has become radioactively contaminated and no longer will be used in such a facility, and
d. radioactive parts of a nuclear facility to be decommissioned.

Loose and fixed contamination

Loose contamination is found on the surface of an object and can be removed by means of simple remedial actions such as wiping or washing. Fixed contamination is integrated into the material and can only be removed with special decontamination methods, for example blasting.

MDA

Minimum Detectable Activity. The minimum activity a system can measure with safety, depending on the desired degree of reliability, background level, measurement instrument efficiency and measurement time.

Dismantling and demolition

Based on SSMFS 2008:1, Chapter 1 § 2, Chapter 9 § 6–8. The period during decommissioning that requires a report according to article 37 in the Euratom treaty and a revised safety analysis report with respect to the planned activities. During this period, decontamination, dismantling and demolition of the facility is performed to such an extent that the quantity of radioactive elements decrease to levels that permit clearance.

See also the definition of **Demolition**.

Nuclide vector

A nuclide vector is used to calculate the activity for nuclides that are not measured directly. This is done by relating the activity of the vector nuclides, by means of a factor, to either a measured nuclide, or to a total measurement of an activity type in a specific system or a delineated area.

Independent inspection

An inspection performed by an internal or external competent and independent resource, that has not previously been involved in the management of the specific case.

Object

Refers to a system, a surface or an area that is defined and has been delineated in extent. It can consist of all or parts of the system/system identity, surface or area.

Operational limit

Limit for measurement with hand-held instruments when the object (material, room, building or land) is so contaminated that clearance cannot take place. The measurements should be interrupted for remedial action if the operational limit is reached.

Count rate equipment

Equipment that measures the number of alpha and/or beta particles that hit the active surface of the instrument. Certain count rate instruments can also measure gamma radiation. Mostly used for measurement of surface contamination.

Radiation protected area

See also **Protected area**.

Representative sampling/measurement

Sampling/measurement aimed to create a representative picture of the whole.

Targeted sampling/measurement

Sampling/measurement with a specific purpose, for example inspection of areas with greater risk of radioactive contamination than others.

The concept of risk

Risk is a measure of the harmful effects of a future event. Risk is usually, even if there is no generally accepted definition, defined as a function of

- the probability that a certain event occurs and
- the consequence of the occurrence of this event.

The probability of a detrimental event multiplied by an evaluation of damage is the usual meaning of risk in technical applications. In a clearance context, the expression "risk" mostly refers to probability. The parameter consequence is, however, not in any way unimportant.

The consequence of incorrect clearance can in an extreme case pose a potential threat to human health, animals and the environment. Such a scenario is very unlikely. A more likely potential consequence of incorrect clearance is reduced confidence from regulatory authorities, recipients of cleared material and the public.

Risk categorisation

Division of objects and areas into categories based on the risk of radioactive contamination:

- **Extremely small risk of contamination** – materials, rooms or buildings where, based on the assessment, there has not been any risk of radioactive contamination and which thus can be assumed to be free of contamination.
- **Small risk of contamination** – materials, rooms or buildings where there may have been a risk of radioactive contamination, but that on good grounds can be assumed to be clean.
- **Risk of contamination** – materials, rooms or buildings where there is or has been a risk of radioactive contamination.
- **Contamination above the clearance limit** – radioactive contamination above the clearance limit.

Dismantling

In the European Commission's recommendation (2010/635/Euratom) regarding application of article 37 in the Euratom treaty, there is a definition of dismantling which reads:

"Within these activities dismantling comprises disassembling, cutting and demolition of contaminated or activated components, systems and structures including their packaging and transfer off-site."

The concept of dismantling can thus be said to replace demolition until the facility or part of the facility is cleared. This is followed by demolition of cleared parts, which then entails conventional demolition.

Remedial action

Remedial action is a simpler form of decontamination and includes wiping or washing.

Stratification

Division of an object into subareas.

Protected area

According to the regulation SSMFS 2008:51. A work place that is covered by the regulations and that is not **Controlled area**, i.e. where the annual effective dose may be 1–6 mSv. NB, not to be confused with **Protected area** according to SSMFS 2008:12 (physical protection).

Sampling

Random, targeted or systematic inspection/information collection in order to create a representative picture of the whole. For small numbers of samples there is large uncertainty. Targeted (via instruction/procedure) and systematic sampling is preferred above random sampling.

Smear test

Sampling and assessment of loose surface contamination according to ISO-SS 7503-1.

Radiation protection check

Refers to scanning with for example smear test, measurement square or probe in order to check the clearance condition linked to total specific surface activity.

Total activity

The total amount of radioactivity for an object.

Conditional clearance

Clearance with special conditions, according to for example RP89.

Surface activity

Activity on the surface of an object.

Surface contamination

Radioactive contamination on the surface.

A2 Symbols in mathematical formulas

Symbol	Meaning
C_i	Surface- or mass-specific activity for nuclide *i*
C_{FNi}	Surface- or mass-specific clearance level for nuclide i
Y_D	Detector efficiency (scintillation detector)
r_N	Net count rate
ρ_N	Net count rate in a single measurement
b_R	Clearance constant
$\bar{x}$	Estimation of the mean value for the variable x
s_x	Estimation of the standard deviation for the variable x
μ_x	Expected value for the variable x
σ_x	Standard deviation for the variable x
n	The number of measurements or samples
v	The number of degrees of freedom
t	A variable whose random variation follows a t-distribution
z	A variable whose random variation follows a standard normal distribution

Appendix B

Measurement and sampling equipment

B1 Measurement and sampling equipment − examples

This appendix provides examples of measurement and sampling equipment for radiological survey and clearance measurement. A concrete example from a Swedish project is described. The project selected is phase 3 in the decommissioning of R2 in Studsvik, which includes the entire R2 facility (Figure B-1), except the reactors (Phase 1) and the biological shield (Phase 2). Both a radiological survey and clearance measurement needs to be carried out in the entire facility before clearance can occur.

B1.1 System overview

The R2 facility in Studsvik includes ten buildings and about 250 rooms. All buildings, rooms and room areas are stored in the database SVALA in a tree structure. Other objects can be included in a room area, for example a square for measuring or objects in the room that belong to the area. Service systems are also included in the tree structure. Part of the tree structure is shown in Figure B-2.

An inventory was made in the facility in order to, foreach room, specify the quantity of surfaces and what objects belonged to each surface. An initial risk categorisation according to a five-point scale (from *extremely small risk of contamination* to *risk of contamination* and another category for *non-clearable*) was carried out for all rooms, which is also stored in SVALA. The initial risk categorisation is also linked to a planned measurement and sample programme in SVALA, whose extent increases with increasing risk. In SVALA, it is possible to continuously see how many planned measurements and samplings are included in the survey, and how many completed measurements and samplings there are.

Registration in SVALA is made directly in the database, i.e. Internet access is needed when objects are added or edited, or when measurement data files are uploaded.

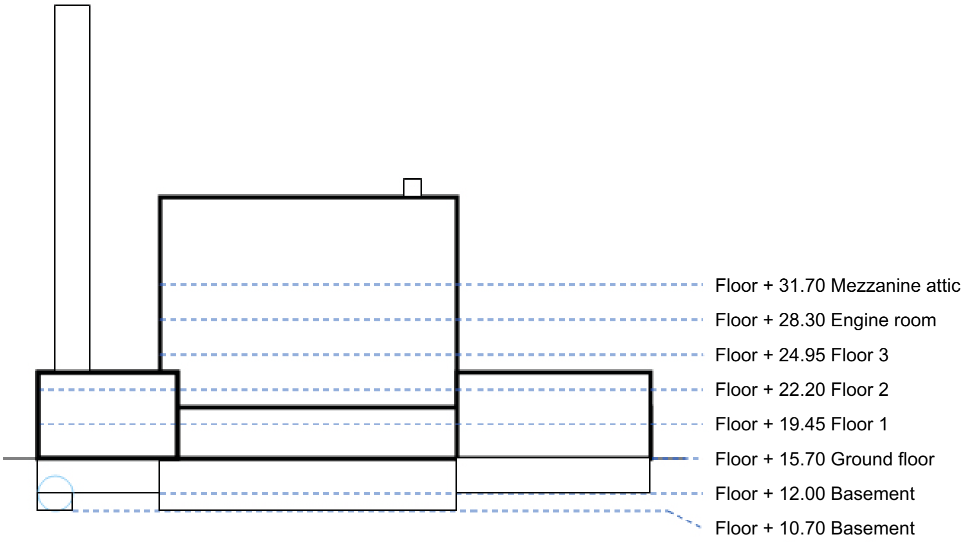
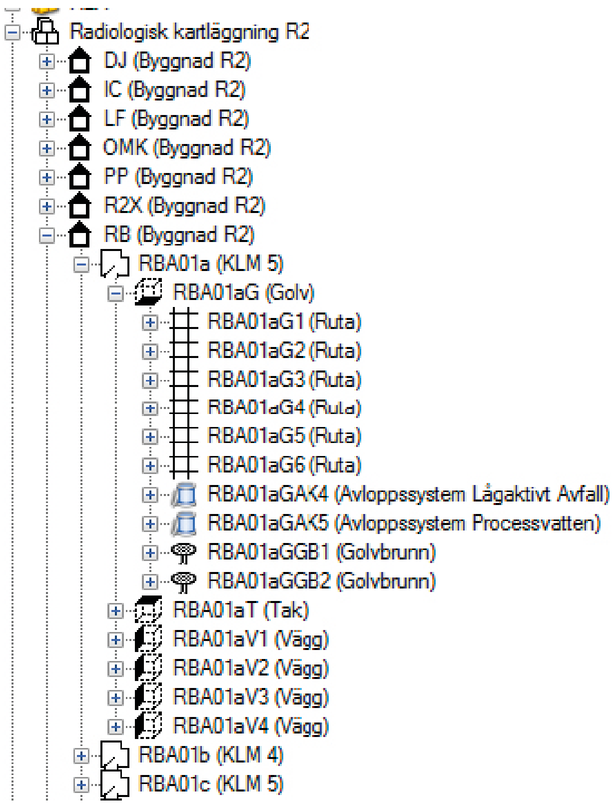


Figure B-1. *Picture of the R2 facility and its floors.*



- Radiologisk kartläggning R2
  - DJ (Byggnad R2)
  - IC (Byggnad R2)
  - LF (Byggnad R2)
  - OMK (Byggnad R2)
  - PP (Byggnad R2)
  - R2X (Byggnad R2)
  - RB (Byggnad R2)
    - RBA01a (KLM 5)
      - RBA01aG (Golv)
        - RBA01aG1 (Ruta)
        - RBA01aG2 (Ruta)
        - RBA01aG3 (Ruta)
        - RBA01aG4 (Ruta)
        - RBA01aG5 (Ruta)
        - RBA01aG6 (Ruta)
        - RBA01aGAK4 (Avloppssystem Lågaktivt Avfall)
        - RBA01aGAK5 (Avloppssystem Processvatten)
        - RBA01aGGB1 (Golvbrunn)
        - RBA01aGGB2 (Golvbrunn)
      - RBA01aT (Tak)
      - RBA01aV1 (Vägg)
      - RBA01aV2 (Vägg)
      - RBA01aV3 (Vägg)
      - RBA01aV4 (Vägg)
    - RBA01b (KLM 4)
    - RBA01c (KLM 5)

Figure B-2. *Part of the radiological survey tree in SVALA for the R2 decommissioning project.*

SVALA was introduced in 2006 by AB SVAFO (SVAFO) and Studsvik Nuclear AB (SNAB) for all waste management, and has through the years been updated with new functionality and to meet new clearance requirements. Today, there are a number of different functions implemented in SVALA, for example

- personal role-based login,
- project-specific input for waste and transports,
- measurement data are integrated automatically from external equipment, for example drum measurements,
- daily QA inspections of the database to find incorrect registrations,
- different types of reports and search forms,
- complete nuclide vector management at different levels (company, order, transport, container, packaging or waste item),
- transport logging internally and externally e.g. to SKB,
- clearance of materials according to SSMFS2011:2,
- traceability of waste from decommissioning projects,
- positioning system for measurements and sampling from decommissioning projects.

Today SVALA is a valuable tool for all waste management and radiological survey at SVAFO and SNAB. SVALA is used daily in all facilities that generate, manage or condition waste at Studsvik, as well as for the facilities in decommissioning. Development of functionality in SVALA is still in progress, since the activities change. SVALA's availability through the years has been good.

B1.1.1 Premises

Prior to the practical part of the survey, an initial assessment and risk categorisation were made based on knowledge of the facility and its history. The assessment was documented in a separate report which is a basis for the subsequent survey measurements.

The database SVALA had before the R2 decommissioning been used for radiological survey in Ranstad, and for the R2 survey the database functionality was extended to further ensure the quality of data. A positioning system that uses RFID tags was part of the added functionality.

The radiological survey was described in a number of instructions, for example

- naming of rooms, systems and objects,
- registration of rooms, systems and objects in SVALA,
- assembly principles for RFID and registration in SVALA,
- measurements at radiological survey,
- loading of measurement data to SVALA,
- sampling at radiological survey,
- registration of equipment and users for radiological survey in SVALA.

It is important to keep the existing roles and responsibilities apart at the execution of radiological survey. In SVALA, roles are defined for the following radiological survey work:

- Measurement technician.
- Reviewer.
- Approver.
- Administrator.

The roles have different responsibilities during radiological survey and are used to quality-assure data in the project. Administrators have increased database access in order to administer the database.

B1.1.2 Measurement equipment

In the project, monitoring equipment that can collect data in files for direct transfer to SVALA are used. The project has chosen to focus on measurements with Canberra Colibri for the following reasons:

- Personal login makes it clear who is measuring.
- Possibility to configure several units in the same way guarantees that all measurements are the same.
- Possibility to connect up to eight probes simultaneously gives more efficient measurement.
- Integration with RFID tags eliminates the need for manual positioning.
- Integrated GPS provides a good complement for outdoor measurements.
- The measurement data file contains detailed information on who has measured what and when, as well as the serial number and calibration status of used equipment (the same file format for up to eight probes).
- A web server can be used for access to data and configuration.

Figure B-3 gives examples of equipment used in the project. Two different RFID tags are used, one model that can be welded into the floor where forklifts will drive and another model that can be glued or screwed on. A piece of equipment (*vita klubban*) is used to read the ID of RFID tags and communicates with the Canberra Colibri equipment via Bluetooth. RFID tags must be assigned to each object in the survey tree in SVALA, this can be done in advance via a USB-connected reader, or directly in the facility if new objects need to be created. The project has chosen several different scintillation detectors for different purposes, among others Canberra Smart Probe SAB-100 and Thermo DP8 are used.

Figure B-3. Measurement equipment used for radiological survey in the R2 decommissioning project.

B1.1.3 Sampling equipment

The equipment used in the documentation of sampling is shown in Figure B-4. The same type of RFID tags that are used in measurements are placed where sampling will take place. During the sampling, a hand-held computer reads the RFID tag ID, which is then printed as a bar code on a sticker with the connected printer. The sticker is attached to the bag in which the sample has been placed. The bar code is read at the analysis laboratory, and the same ID is included in the report of results from the analysis laboratory to SVALA. If SVALA cannot find the ID for a result sent by the analysis laboratory, SVALA sends out a notification by e-mail. In this way, it can be guaranteed that the results match the current survey.

B1.1.4 Positioning

RFID tags are used to automatically position the location where measurement or sampling occurred. No manual registration is needed to provide a valid position in the facility during measurement or sampling. Since a large radiological survey often includes thousands of positions for measurement and sampling, it is easy to confuse positions if manual registration is required. Positioning by means of RFID tags increases the quality of the efforts and reduces the work time and thereby the costs.

B1.1.5 QA

Quality assurance of the activities during radiological survey or clearance measurement is determined to a great extent by the QA system that is in place and applied in the project. The efforts, both measurement and sampling as well as further data processing and evaluation, should be controlled by instructions in order to define the work clearly and make it possible for others to repeat.

All involved roles and their responsibilities need to be similarly defined and described as a part of the project.

All documentation within the project should live up to the company's internal review and other requirements.

Ensure that all equipment is calibrated before the project starts.

Figure B-4. *Equipment to document where sampling takes place in the facility.*

B1.2 Practical implementation

In order to practically implement radiological survey and clearance measurement, the following is required:

- A first survey report with initial risk categorisation of all rooms.
- Inventory of all buildings and rooms.
- Buildings and rooms are emptied of loose equipment.
- Initial measurement and sampling programme for each assessed risk level:
  - How much must be measured and sampled?
  - What should be measured and sampled?
  - How should it be measured and sampled?
  - Is the statistical evaluation prepared?
- Inventory objects transferred to the database survey tree:
  - At the same time, upload photos from each room or object so that they are accessible from the survey tree.
- Measurement and sampling equipment that is tested for the task:
  - Sufficient integration time at measurement.
  - Sufficiently low MDA for measurement equipment.
- Approved nuclide vectors for the facility concerned.
- Clearance levels transferred to the current measurement and sampling equipment.
- Database tested for the task.
- Instructions for all relevant parts.
- Trained personnel for measurement and sampling, database management, evaluation and reporting.

- Dedicated work force for the different roles:
  - Measurer.
  - Reviewer.
  - Approver.
  - Administrator.
  - Evaluation of the results.
  - Writing of reports.
  - Material from authorities.
  - Redundancy for the different roles.
- RFID tags are placed in the facility in conjunction with measurement or sampling, or in advance if possible.
- A realistic timetable.

For clearance measurement it is also required that levels are calculated for which actions are required, taking into account the statistical uncertainty. These levels need to be available during clearance measurement, so that measurement personnel can react directly when clearance measurements are conducted.

There may be a need to conduct several measurements on the same object in order to get an idea of the spread in data, and to compare different equipment/measurement teams. A certain amount of repeated targeted measurements and some repeated random measurements may be needed. The extent of the repeated targeted and random measurements may be in the order of 1−3 % each.

B1.2.1 Measurements

Measurements need to be carried out both indoors and outdoors during both radiological survey and clearance measurement. With Canberra Colibri, two different types of measurements are prepared:

1. Scannig measurements with one (or more) large scintillation detectors (DP8):
   - Used for the vast majority of floor surfaces and wall surfaces up to 2m during radiological survey, in order to get a radiological overview of the state of the facility.
   - A RFID tag is placed on each surface area that will be measured.
   - The measurement is performed with Canberra Colibri and with one to eight DP8-probes connected in parallel.
   - The DP8-probes are scanned over the measured surface in a pattern and at a rate controlled by instructions.
   - Measurement files are transferred to SVALA daily and are continuously evaluated.
   - Mean value calculation is carried out in SVALA, which also saves the maximum value.
   - Elevated activity is marked to possibly be measured in more detail as a delineated square.
   - Figure B-5 shows a simple measurement device with two DP8-probes installed.
2. The entire surface of a delineated square is measured with an alpha-beta scintillation detector (Canberra SAB-100) and longer integration time for each measurement (for example 20 s):
   - Altogether, 32 measurements are required to cover the square, which gives 32 alpha and 32 beta values.
   - This type of measurement can be used when more accurate measurement of individual areas is needed.
   - A RFID tag is placed in the square.
   - Mean value calculation for the square is carried out in SVALA, which also saves the maximum value.
   - Figure B-6 shows what a square may look like.
   - Figure B-7 shows the results in SVALA from measurement of a square.

At the same time as measurement takes place with scintillation detectors, Canberra Colibri also measures dose rates.

Figure B-5. Measurement device with room for two DP8 scintillation detectors installed for scanning measurement of floor surfaces. Measurement data from both probes are collected in a Colibri measurement data file.

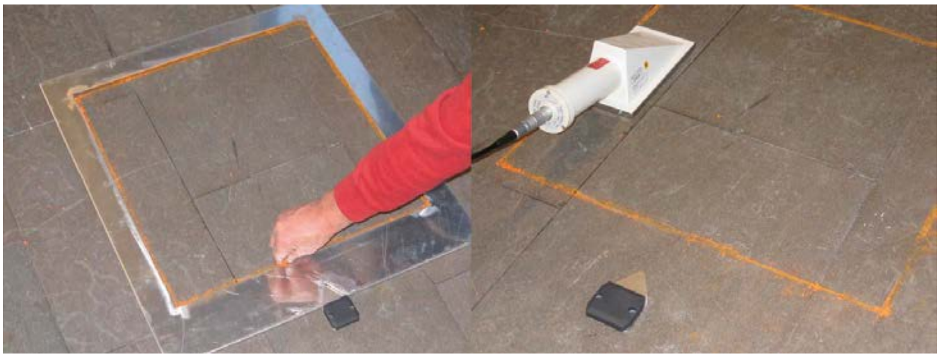
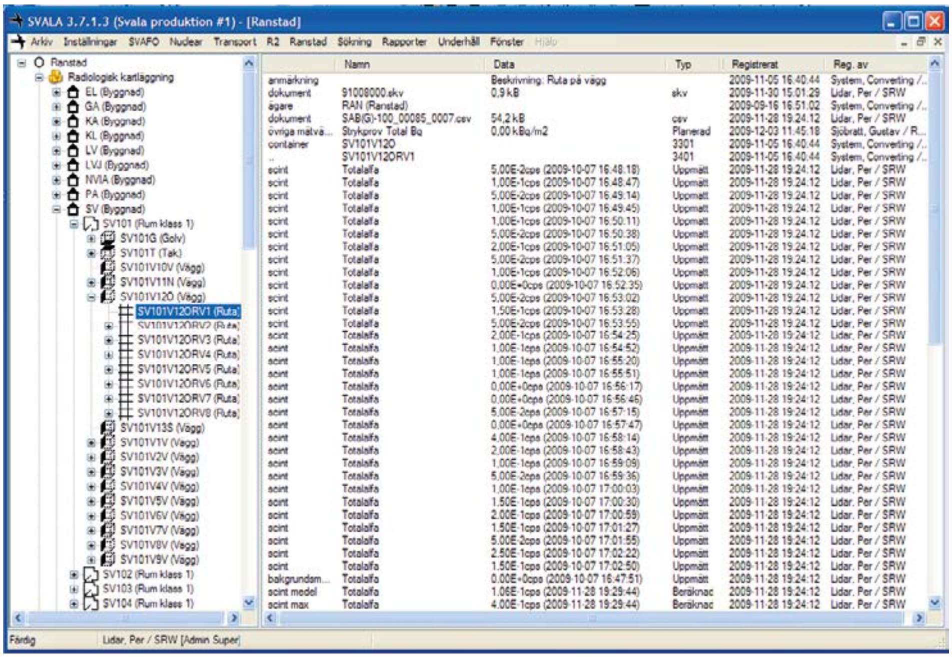


Figure B-6. Square for more accurate measurement with the scintillation detector Canberra SAB 100.



- Ranstad
  - Radiologisk kartläggning
    - EL (Byggnad)
    - GA (Byggnad)
    - KA (Byggnad)
    - KL (Byggnad)
    - LV (Byggnad)
    - LVJ (Byggnad)
    - NVIA (Byggnad)
    - PA (Byggnad)
    - SV (Byggnad)
      - SV101 (Rum klass 1)
        - SV101G (Golv)
        - SV101T (Tak)
        - SV101V10V (Vägg)
        - SV101V11N (Vägg)
        - SV101V12O (Vägg)
          - SV101V12ORV1 (Ruta)
          - SV101V12ORV2 (Ruta)
          - SV101V12ORV3 (Ruta)
          - SV101V12ORV4 (Ruta)
          - SV101V12ORV5 (Ruta)
          - SV101V12ORV6 (Ruta)
          - SV101V12ORV7 (Ruta)
          - SV101V12ORV8 (Ruta)
        - SV101V13S (Vägg)
        - SV101V1V (Vägg)
        - SV101V2V (Vägg)
        - SV101V3V (Vägg)
        - SV101V4V (Vägg)
        - SV101V5V (Vägg)
        - SV101V6V (Vägg)
        - SV101V7V (Vägg)
        - SV101V8V (Vägg)
        - SV101V9V (Vägg)
      - SV102 (Rum klass 1)
      - SV103 (Rum klass 1)
      - SV104 (Rum klass 1)

	Namn	Data	Typ	Registrerat	Reg. av
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ägare	RAN (Ranstad)			2009-09-16 16:51:02	System, Converting /...
dokument	SAB(G)-100_00085_0007.csv	54,2 kB	csv	2009-11-28 19:24:12	Lidar, Per / SRW
övriga mätvä...	Strykprov Total Bq	0,00 kBq/m2	Planerad	2009-12-03 11:45:18	Sjöbratt, Gustav / R...
container	SV101V12O		3301	2009-11-05 16:40:44	System, Converting /...
..	SV101V12ORV1		3401	2009-11-05 16:40:44	System, Converting /...
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scint	Totalalfa	1,00E-1cps (2009-10-07 16:55:20)	Uppmätt	2009-11-28 19:24:12	Lidar, Per / SRW
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scint	Totalalfa	0,00E+0cps (2009-10-07 16:57:47)	Uppmätt	2009-11-28 19:24:12	Lidar, Per / SRW
scint	Totalalfa	4,00E-1cps (2009-10-07 16:58:14)	Uppmätt	2009-11-28 19:24:12	Lidar, Per / SRW
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scint	Totalalfa	1,00E-1cps (2009-10-07 17:00:03)	Uppmätt	2009-11-28 19:24:12	Lidar, Per / SRW
scint	Totalalfa	1,50E-1cps (2009-10-07 17:00:30)	Uppmätt	2009-11-28 19:24:12	Lidar, Per / SRW
scint	Totalalfa	2,00E-1cps (2009-10-07 17:00:59)	Uppmätt	2009-11-28 19:24:12	Lidar, Per / SRW
scint	Totalalfa	1,50E-1cps (2009-10-07 17:01:27)	Uppmätt	2009-11-28 19:24:12	Lidar, Per / SRW
scint	Totalalfa	5,00E-2cps (2009-10-07 17:01:55)	Uppmätt	2009-11-28 19:24:12	Lidar, Per / SRW
scint	Totalalfa	2,50E-1cps (2009-10-07 17:02:22)	Uppmätt	2009-11-28 19:24:12	Lidar, Per / SRW
scint	Totalalfa	1,50E-1cps (2009-10-07 17:02:50)	Uppmätt	2009-11-28 19:24:12	Lidar, Per / SRW
bakgrundsm...	Totalalfa	0,00E+0cps (2009-10-07 16:47:51)	Uppmätt	2009-11-28 19:24:12	Lidar, Per / SRW
scint medel	Totalalfa	1,06E-1cps (2009-11-28 19:29:44)	Beräknad	2009-11-28 19:24:12	Lidar, Per / SRW
scint max	Totalalfa	4,00E-1cps (2009-11-28 19:29:44)	Beräknad	2009-11-28 19:24:12	Lidar, Per / SRW

Figure B-7. Measurement data for the blue-marked square are shown in the right window.

B1.2.2 Sampling

Sampling needs to be carried out both indoors and outdoors during both radiological survey and clearance measurement. Several types of sampling are described in the instructions and SVALA is prepared to both record the samples and receive result files from evaluation. Current sampling types are:

- material samples,
- drilling samples,
- drill core samples,
- water samples.

B1.2.3 Scalability

There may be a difference of a factor of hundred between the number of measurements and samples for radiological survey compared with clearance measurement, which needs to be taken into account. Primarily, the time required to carry out all measurements and take all samples is affected. Some time can be saved by using already established methods (equipment, database, evaluation).

B1.3 Experience feedback

Although the R2 decommissioning project is ongoing and radiological survey is not yet completed, an experience feedback can, nevertheless, be made for efforts completed so far.

B1.3.1 Development of systems

The version of SVALA for radiological survey used by the R2 decommissioning project is a development of the version that was used for radiological survey in Ranstad 2009–2010. The evaluation after Ranstad radiological survey showed that SVALA worked well for receiving large amounts of data from equipment but that some functionality was missing. The absence of a positioning system was noted, and better possibility to search for samples and measurements was also required.

The SVALA functionality and the positioning system in itself took half a year to develop (from start to delivery), but the longest time was spent on trying to get one of the major equipment manufacturers to integrate support for the RFID industry standard selected (there are three RFID standards). The equipment manufacturer needed more than a year to implement RFID support for the equipment that was included in the positioning system.

B1.3.2 Life of data

By having quality assured data already from radiological survey, the life of these data can be prolonged and permit savings later in the project. A common approach in previous projects has been that radiological survey data are not used for anything else than radiological survey, and thereby the life of data was short.

B1.3.3 Competence and resources for data processing

Stricter processing of data, and a more instruction-controlled implementation of radiological survey entails a longer starting distance for the project. More training and some innovative approaches are required in particular as personnel with different experiences meet in a new way of working.

The experience so far is nevertheless that all those involved strive for the same goals and help each other to obtain a system and a management that work in reality. One goal in itself has been to reduce the number of manual registrations that need to be made during radiological survey to a minimum, previous experience shows that there will be incorrect registrations in a small part, and that it can be difficult to know which part this is, which can in itself reduce the credibility of the procedure and results.

B1.3.4 QA

The experience so far in the R2 decommissioning project is that the increased ambition in terms of quality assurance will pay off in the long term, although the start-up time is longer compared with radiological survey in previous projects. It is also decided that systems developed for the R2 decommissioning project will be used by SVAFO for other future projects. Thereby, a greater synergy effect can be obtained since personnel and procedures are already familiar with the existing systems.

Appendix C

Information management and software support

C1 Information management and software support

This appendix describes information management and software support for radiological survey and clearance measurement.

C1.1 Information chain

Many software applications need to exchange information in a larger project and in a company. The data collected and processed in radiological survey and clearance measurement will be needed in other contexts, both within and outside of the project and company. It is therefore important that the software for radiological survey and clearance measurement both can collect data from other systems and submit information to other systems, this often needs to take place on short notice to get the current status.

C1.2 Quality in each step

In the entire information chain, it is important that the information has the right quality in each step. The right quality does not only entail that the data are quality assured, but also that those who evaluate and interpret information have the right knowledge and make the correct interpretation, and that data are presented and reported correctly.

Quality in each step needs to permeate the control programme for radiological survey and clearance measurement.

C1.3 Integrated information management

In order to get an information chain with quality in each step, integrated information management is required. Information gathered in a system should not need to be manually transferred to another system, the systems used should be able to import and export information to a reasonable extent. In practice, it turns out that the same information is often needed in several systems.

C1.4 Examples from reality

Figure C-1 shows an example from Studsvik of how integrated information management is used. A large quantity of data are needed in SVALA for waste management projects, such as transport and waste information. For decommissioning project, the corresponding radiological survey information is needed. From SVALA information needs to be exported within the project and as a basis for reports to authorities.

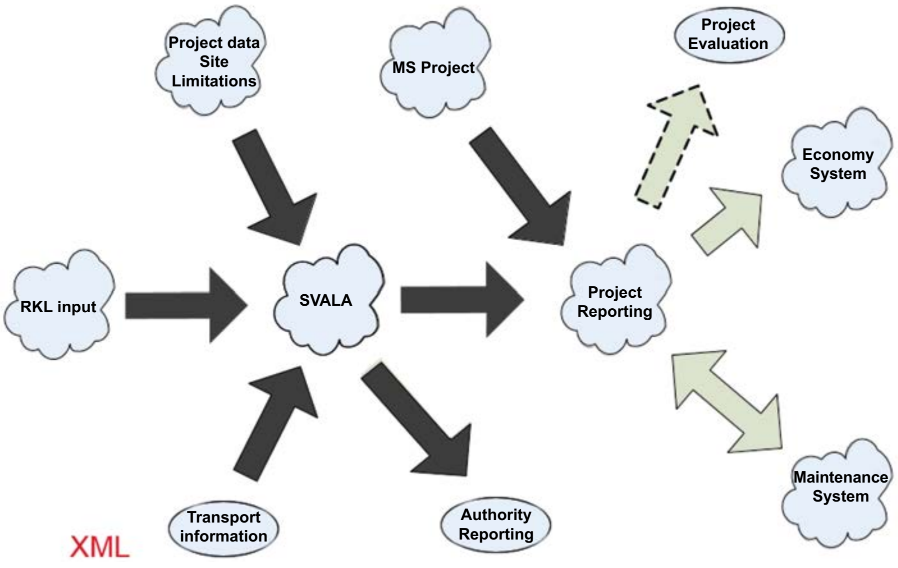
C1.5 Experience from previous projects

The experience from previous projects regarding integrated information management for decommissioning projects is rather limited in Sweden. Fairly recently completed decommissioning projects include ACL in Studsvik and the Ranstad plant.

The ACL project started to use a database for measurement and sampling data during the course of the project, but did not consider the issue from the beginning.

For decommissioning in Ranstad, different actors have participated through the years, with different approaches to and different focus on how integrated information management is best performed.

The decommissioning of the Studsvik R2 reactor is under way and decommissioning in Barsebäck is being prepared. In these projects, integrated information management has come furthest, but there is more to be done in order to obtain optimal information management during decommissioning.



Figur C-1. *Information from radiological survey and clearance measurement needs to be integrated in several other systems. Where large quantities of information need to be moved between different databases, this is preferably done with XML standards.*

From the experience abroad, two examples can be mentioned:

1. ENRESA has for the decommissioning of NPP José Cabrera integrated information management fairly far, and has had a pronounced goal to quality-assure the information during the project [ICEM2013-96227].
2. SCK-CEN has for the decommissioning of NPP BP3 and the fuel factory Belgo Nucleaire developed an information management similar to SVALA in order to achieve good traceability for the waste from the projects. See further [ICEM2013-96317].

Appendix D

Survey and clearance measurement in a hypothetical facility

This appendix describes the extent of a radiological survey and clearance measurement in a hypothetical facility.

D1 The facility

The facility was used for radiological activities during many years, but is now taken out of service and will be demolished after clearance. When the facility was taken out of service, it contained rooms from all risk categories, from *extremely small risk of contamination* to *not subject to clearance*, see Table D-1, where a risk category has been assigned to each room based on the conducted activities. There is no land belonging to the facility, all operation has occurred indoors. The total floor area in the facility is about 2,500 m^2, of which about 70 m^2 are non-controlled areas.

D1.1 Facility description

The building was constructed in the 1960s with an extension that connects directly to the house on the western side (another nuclear facility on the same site), and has housed activities involving handling of irradiated samples. Some of the rooms were used as offices and conference rooms. The building is constructed in four floors (about 31 × 20 m per floor) and primarily included the following rooms:

- At the basement floor: Workshop, with some machinery, active laboratory, isotope laboratory, sample bank and culverts for active sewerage, in addition rooms such as heating central and switchgear.
- At the ground floor: Rooms for lead cells, storerooms for transport protection, storage and offices.
- At the upper floor: Offices and activation laboratories.
- At the attic floor: Fans and filters for active ventilation and fans for the pneumatic tube conveyor system, as well as areas for placement of waste.
- Entrance, corridors and changing rooms are used jointly for the operating companies.

D1.2 Activity description

At the facility, handling of different substances before and after irradiation was performed. Preparations prior to and handling after irradiation of isotopes was carried out. The isotopes were then placed in transport protection. Handling in the cells and gloveboxes has been a part of the daily activities.

Systems in the facility are:

- Active ventilation system.
- Active sewerage system.
- Power supply.
- System for isotope activities.
- There is a pneumatic tube conveyor system, approximately 100 m long, which connects the irradiation location and the receiving cell in the building.

General supply systems are:

- Ventilation system.
- Sewerage system.
- Heating system.
- Deionised water system.
- Pure water system/city water system.
- Cooling water system (freshwater).
- Compressed air system.
- Electrical systems.

D1.3 Events at the facility and systems associated with the building

The rooms in the building that have been used for the activities are expected to have a relatively high degree of contamination in relation to the mean value of the Swedish nuclear facilities.

Flooding has occurred in the basement, as well as small pipe leakage.

Insofar as there is historical contamination, it stems from previous activities and there are surfaces in the floor that contain contamination but were painted over during previous renovations.

In the basement workshop, various materials were processed. There is, however, some risk that Co-60, now painted over, is left in the walls.

The ventilation system can be feared to be contaminated, since some breakthrough through the filters from each installation may have arisen through many years of use.

The pneumatic tube conveyor system that connects a location in the reactor and the receiving cell at the facility is feared to be highly contaminated on the inside.

In some areas there might be contamination in the floor's surface layer. The floor surface was under frequent maintenance and can therefore hide contamination via repeated epoxy layers.

The risk of *hot spots* in the facility are small except in used cells, where *hot spots* occur.

D2 Radiological survey and clearance measurement

The strategy for the radiological survey follows the description in Chapter 4 and 7 of the report. The focus is on work according to DQO. Radiological survey will result in a division of the facility into homogeneous packages. Parts that are homogeneous with respect to risk category, nuclide vector, contamination occurrence and degree of contamination. The strategy for clearance measurement follows the description in Chapter 7 of the report.

D2.1 Division into risk categories

The following division into risk categories is made for the different rooms in the facility:

Table D-1. The facility's rooms per risk category.

Risk category	Number of rooms	Approximate floor surface/m^2
Extremely small risk of contamination	2	70
Small risk of contamination	3	100
Risk of contamination	23	790
Contamination above the clearance limit	36	1 230
Not subject to clearance	9	310

D2.2 Measurement and sampling

The type of measurement and sampling that is intended to be carried out during radiological survey and clearance measurement is shown in Table D-2. The measurements consist of count rate and dose rate measurements, as well as measurements with ISOCS. Sampling consists of smear samples, material samples, drilling samples (gives a powder as a sample) and drill core samples (gives a drill core as a sample).

A large part of the measurements and sampling during radiological survey are targeted systematic efforts based on the facility's history. The random radiological survey measurements are mainly count rate measurements in grids on the floor and walls. During clearance measurement the measurements are systematic and comprehensive.

If radiological survey measurements are conducted randomly after stratification, the measurements can also be used for clearance if no remedial action is needed. This means that not as many measurements are needed for clearance measurement. This possibility is not included below.

The extent of the measurements and sampling is shown in Table D-3. The total number of samples or measurements for each row in the table is the sum of Number per Room and Number per Object multiplied by Number of objects.

Table D-2. Sampling and measurement during radiological survey and clearance measurement.

Risk category	Phase	Sample/measurement	Where	Comment
Extremely small risk	Radiological survey	E A		
	Clearance measurement	E A		
Small risk	Radiological survey	Smear sample	The room's most loaded surface	Assume floor
	Radiological survey	Smear sample	Surfaces nearest the categorised zone	Assume floor + two walls
	Radiological survey	Count rate	Random samples at the room's most loaded surface	Assume floor
	Radiological survey	Count rate	The room's general level	Background value. Assume middle of floor
	Clearance measurement	Count rate	Random samples at the room's most loaded surface	Assume floor in empty room
	Clearance measurement	Smear sample	As for radiological survey	Assume floor in empty room
Risk	Radiological survey	Smear sample	Combined sample for all inlet channel ventilation	
	Radiological survey	Smear sample	Outlet channel ventilation	
	Radiological survey	Smear sample	The room's most loaded surface	Assume floor
	Radiological survey	Smear sample	Surfaces nearest the categorised zone	Assume floor + two walls
	Radiological survey	Count rate	Grid with a combined measurement (e.g. 20 s) per m^2	Assume floor + two m up on the walls
	Radiological survey	Material sample	Combined sample on the room's most loaded surfaces	Assume floor
	Radiological survey	Material sample	One smear sample per sewer	
	Radiological survey	Dose rate	The room's general level	Assume middle of floor
	Radiological survey	ISOCS	In representative rooms to determine nuclide vector	
	Clearance measurement*	Count rate	Slow scanning measurement over the entire surface (all m^2)	Floor + walls up to 2 m. Use op. limit value cps
	Clearance measurement*	Smear sample	As for radiological survey	
	Clearance measurement*	Material sample	One smear sample per sewer	
Contamination above the clearance limit	Radiological survey	Material sample	Sludge from tanks and containers in room	
	Radiological survey	Material sample	Targeted actions	
	Radiological survey	Material sample	One smear sample per sewer	
	Radiological survey	Smear sample	Combined sample for all inlet channel ventilation	
	Radiological survey	Smear sample	Outlet channel ventilation	
	Radiological survey	Material sample	Drilling sample if deep contamination is suspected	Add manually if necessary
	Radiological survey	Count rate	Random samples at the room's most loaded surface	Assume floor + two m up on the walls
	Radiological survey	Dose rate	The room's general level	Assume middle of floor
	Radiological survey	Count rate	On systems and equipment in the room	
	Radiological survey	Dose rate	On systems and equipment in the room	
	Radiological survey	ISOCS	In representative rooms to determine nuclide vector	
	Clearance measurement	E A		No sampling or measurements will be performed
Not subject to clearance	Radiological survey	Material sample	Sludge from tanks and containers in room	
	Radiological survey	Material sample	Targeted actions	
	Radiological survey	Material sample	One smear sample per sewer	
	Radiological survey	Smear sample	Combined sample for all inlet channel ventilation	
	Radiological survey	Smear sample	Outlet channel ventilation	
	Radiological survey	Material sample	Drill core sample for deep contamination and induced activity	Add manually if necessary
	Radiological survey	Count rate	Random samples at the room's most loaded surface	Assume floor
	Radiological survey	Dose rate	The room's general level	Assume middle of floor
	Radiological survey	Count rate	On systems and equipment in the room	
	Radiological survey	Dose rate	On systems and equipment in the room	
	Clearance measurement	E A		No sampling or measurements will be performed

* Also for areas where remedial action has been taken from the initial risk categories Contamination above the clearance limit and Not Subject to clearance.

Table D-3 . Measurement and sampling extent for radiological survey and clearance measurement.

Risk category	Phase	Sample/ measurement	Where	Number/ Room	Number/ Object	Number of objects	Comment
Extremely small risk	Radiological survey	E A					
	Clearance measurement	E A					
Small risk	Radiological survey	Smear sample	The room's most loaded surface	1		3	Assume floor
	Radiological survey	Smear sample	Surfaces nearest the categorised zone	3		3	Assume floor + two walls
	Radiological survey	Count rate	Random samples at the room's most loaded surface	1		3	Assume floor
	Radiological survey	Count rate	The room's general level	20		3	Background value. Assume middle of floor
	Clearance measurement	Count rate	Random samples at the room's most loaded surface	20		3	Assume floor in empty room
	Clearance measurement	Smear sample	As for radiological survey	3		3	Assume floor in empty room
Risk	Radiological survey	Smear sample	Combined sample for all inlet channel ventilation	1		23	
	Radiological survey	Smear sample	Outlet channel ventilation		1	23	
	Radiological survey	Smear sample	The room's most loaded surface	1		23	Assume floor
	Radiological survey	Smear sample	Surfaces nearest the categorised zone	3		23	Assume floor + two walls
	Radiological survey	Count rate	Grid with a combined measurement (e.g. 20 s) per m^2	1		1185	Assume floor + approx. 2 m up on the walls
	Radiological survey	Material sample	Combined sample on the room's most loaded surfaces	1		23	Assume floor
	Radiological survey	Material sample	One smear sample per sewer		1	23	
	Radiological survey	Dose rate	The room's general level	20		23	Assume middle of floor
	Radiological survey	ISOCS	In representative rooms to determine nuclide vector	0.5		23	
	Clearance measurement	Count rate	Slow scanning measurement over the entire surface (each m^2)		20	1185	Floor + walls up to approx. 2 m. Use op.limit cps
	Clearance measurement	Smear sample	As for radiological survey	5	1	23	
	Clearance measurement	Material sample	One smear sample per sewer		1	23	
	Clearance measurement*	Count rate	Slow scanning measurement over the entire surface (each m^2)		20	1845	Floor + walls up to approx. 2 m. Use op.limit cps
	Clearance measurement*	Smear sample	As for radiological survey	5	1	36	
	Clearance measurement*	Material sample	One smear sample per sewer		1	36	
	Clearance measurement**	Count rate	Slow scanning measurement over the entire surface (each m^2)		20	465	Floor + walls up to approx. 2 m. Use op.limit cps
	Clearance measurement**	Smear sample	As for radiological survey	5	1	9	
	Clearance measurement**	Material sample	One smear sample per sewer		1	9	

Risk category	Phase	Sample/ measurement	Where	Number/ Room	Number/ Object	Number of objects	Comment
Contamination above the clearance limit	Radiological survey	Material sample	Sludge from tanks and containers in room		1	36	
	Radiological survey	Material sample	Targeted actions	1		36	
	Radiological survey	Material sample	One smear sample per sewer		1	36	
	Radiological survey	Smear sample	Combined sample for all inlet channel ventilation	1		36	
	Radiological survey	Smear sample	Outlet channel ventilation		1	36	
	Radiological survey	Material sample	Drilling sample if deep contamination is suspected	1		36	Add manually if necessary
	Radiological survey	Count rate	Random samples at the room's most loaded surface	20		36	Assume floor + two m up on the walls
	Radiological survey	Dose rate	The room's general level	20		36	Assume middle of floor
	Radiological survey	Count rate	On systems and equipment in the room	3	1	36	
	Radiological survey	Dose rate	On systems and equipment in the room	3	1	36	
	Radiological survey	ISOCS	In representative rooms to determine nuclide vector	0.5		36	
	Clearance measurement	E A					No sampling or measurements will be carried out until remedial action has been taken in the room, so that it can satisfy the criteria for one of the lower categories.
Not subject to clearance	Radiological survey	Material sample	Sludge from tanks and containers in room		1	9	
	Radiological survey	Material sample	Targeted actions	1		9	
	Radiological survey	Material sample	One smear sample per sewer		1	9	
	Radiological survey	Smear sample	Combined sample for all inlet channel ventilation	1		9	
	Radiological survey	Smear sample	Outlet channel ventilation		1	9	
	Radiological survey	Material sample	Drill core sample for deep contamination and induced activity	1		9	Add manually if necessary
	Radiological survey	Count rate	Random samples at the room's most loaded surface	20		9	Assume floor
	Radiological survey	Dose rate	The room's general level	20		9	Assume middle of floor
	Radiological survey	Count rate	On systems and equipment in the room	3	1	9	
	Radiological survey	Dose rate	On systems and equipment in the room	3	1	9	
	Clearance measurement	E A					No sampling or measurements will be carried out until remedial action has been taken in the room, so that it can satisfy the criteria for one of the lower categories.

*) Cleaned areas with the initial risk category Contamination above the clearance limit.
**) Cleaned areas with the initial risk category Not subject to clearance.

The total amount of measurements and sampling is shown in Table D-4.

It can be concluded from Table D-4 that the amount of measurements during clearance measurement is about a factor of 17 more than during radiological survey.

Table D-4. Total quantity of measurements and sampling during radiological survey and clearance measurement.

Risk category	Phase	Number of samples	Number of measurements
Extremely small risk	Radiological survey	0	0
	Clearance measurement	0	0
Small risk	Radiological survey	12	63
	Clearance measurement	9	60
Risk	Radiological survey	184	1,657
	Clearance measurement	161	23,700
	Clearance measurement*	252	36,900
	Clearance measurement**	63	9,300
Above the clearance limit	Radiological survey	216	1,746
	Clearance measurement***	0	0
Not subject to clearance	Radiological survey	54	432
	Clearance measurement***	0	0
Total:	**Radiological survey**	**466**	**3,898**
	Clearance measurement	**485**	**69,960**

*) Cleaned areas with the initial risk category Above the clearance limit.
**) Cleaned areas with the initial risk category Not subject to clearance.
***) Remedial action must first be carried out down to a lower category.

D2.3 Evaluation of results

Evaluation of results is done by comparing the results (systematic and random) with stipulated clearance levels for buildings and rooms (SSMFS 2011:2).

For the random measurements, special consideration must be given to statistical evaluation to ensure that the uncertainty in the estimate is acceptable.

D2.4 Nuclide vectors

Facility-specific nuclide vectors are determined by means of a combination of ISOCS measurements and laboratory analyses of material samples (for alpha- and beta-emitting nuclides) during radiological survey. Mass spectrum analysis may also be necessary.

D2.5 Information management

All information from measurements and sampling is saved in a database intended for radiological survey and clearance measurement, see Appendix B.

D2.6 Staffing and timetable

Staffing and calender time for radiological survey and clearance measurement has been assessed according to Table D-5. In total, radiological survey is judged to require an effort of 13 person-months during just below one year of calender time. Clearance measurement is judged to require an effort of 19 person-months during just below one year of calender time. It is assumed that more time-efficient measurements can be carried out during clearance measurement, for example with more probes at the same time for one operator.

Table D-5. Estimated staffing and calender time for radiological survey and clearance measurement.

Phase	Step	Staffing (number)	Calender time (months)
Radiological survey	Inventory and risk categorisation	2	2
	Set up the database	1	1
	Planning report radiological survey	2	1
	Prepare measurements and sampling (mark up in the facility)	2	1
	Carry out measurements and sampling	2	1
	Evaluation of results	1	1
	Results report radiological survey	1	1
Clearance measurement	Supporting material to control programme for clearance	2	2
	Prepare measurements and sampling	1	1
	Carry out measurements and sampling	3	4
	Evaluation of results	1	1
	Results report clearance measurement	1	1

Appendix E

Statistical example

E1 Introduction

This appendix describes an example of statistical analysis of a hypothetical clearance measurement for a surface-contaminated object. In the example it is assumed that clearance measurements have been conducted with scintillation equipment, calibrated with respect to total activity through pairwise measurements with a scintillation detector and gamma spectroscopy and a representative nuclide vector determined from analysis of occurring nuclides in a number of material samples.

E2 Determination of parameters

E2.1 Detector efficiency

Detector efficiency (γ_D) has been determined by calibration against gamma spectroscopy measurements in 8 measurement points according to Table E-1.

By plotting quantiles in data, and log-transformed data against standard normal quantiles (Figure E-1), it can be concluded that the log-normal distribution appears to be the better model for describing the uncertainty in data, which can also be seen in calculated p-values for a normal distribution test (Table E-1).

Table E-1 . Determination of scintillation efficiency (γ_D) for 8 independent measurements (p-value refers to Lillliefors normal distribution test).

Measurement	γ_D cps/kBq	ln γ_D
1	1.21	0.19
2	0.83	–0.19
3	2.71	1.00
4	1.40	0.34
5	1.68	0.52
6	1.87	0.63
7	3.88	1.36
8	1.91	0.65
Mean	1.94	0.56
Standard deviation	0.96	0.48
p-value (Lilliefors test)	0.11	0.64

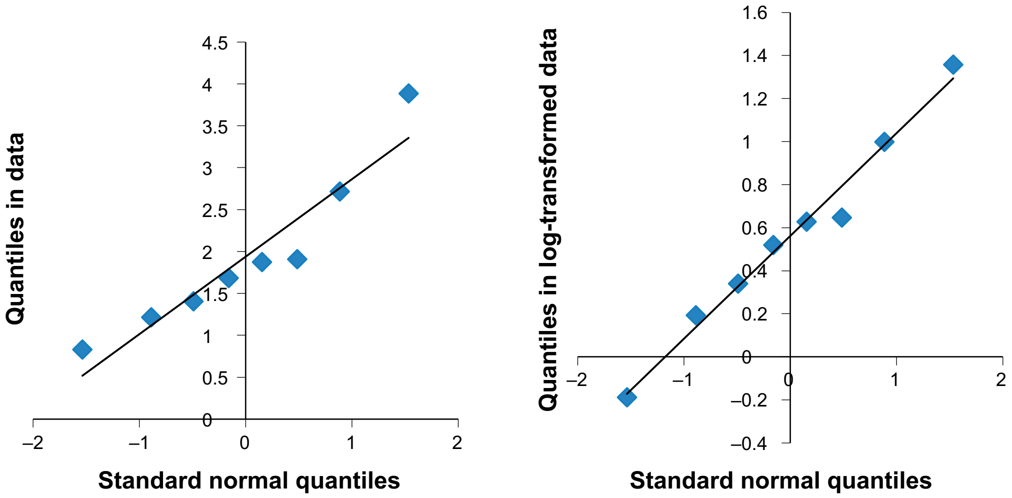


Figure E-1. *Quantile plots with respect to normal and log-normal distribution for scintillation efficiency.*

E2.2 Nuclide vector

The nuclide composition has been determined from 9 material samples. For nuclides that could not be detected, conservative calculated values have been adopted (see Chapter 6 and Appendix 3 in the Clearance Manual (SKB 2011)). From these measurements, 9 values for the clearance constant *b* have been determined (Table E-2). The quantile plot (Figure E-2) and the normal distribution test show that it is reasonable to assume a normal model.

Table E-2. Determination of the clearance constant from the nuclide composition in 8 material samples.

Measurement	*b* Bq/m^2
1	0.0224
2	0.0195
3	0.0180
4	0.0202
5	0.0190
6	0.0142
7	0.0208
8	0.0165
9	0.0246
Mean	0.0195
Standard deviation	0.0031
p-value (Lilliefors test)	0.98

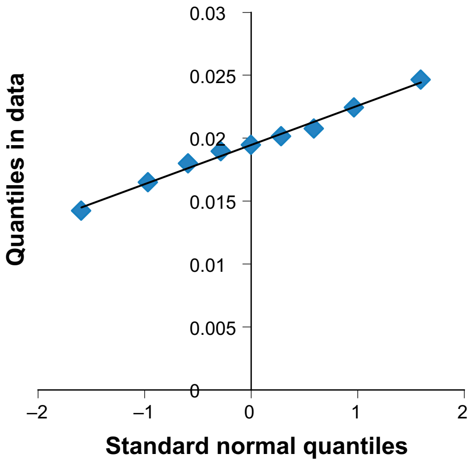


Figure E-2. *Quantile plot with respect to a normal distribution for the clearance constant.*

E2.3 Net count rate

The net count rate (r_N) has been calculated through pairwise measurements in 20 measurement points (Table E-3). The quantile plots (Figure E-3) show that the normal model deviates from the data for low and high values. Therefore the log-normal model is used for analysis of the object's activity level.

Table E-3 . Measured net count rate (ρN) for 20 independent measurements.

Measurement	*ρN* m^2/cps	ln *ρN*
1	8.8	2.2
2	12.1	2.5
3	8.4	2.1
4	0.9	–0.1
5	4.2	1.4
6	1.3	0.3
7	10.3	2.3
8	1.2	0.2
9	2.3	0.8
10	4.3	1.5
11	6.7	1.9
12	25.0	3.2
13	4.2	1.4
14	8.9	2.2
15	2.4	0.9
16	6.9	1.9
17	2.0	0.7
18	6.3	1.8
19	11.6	2.5
20	1.0	0.0
Mean (*rN*)	6.44	1.49
Standard deviation	5.55	0.92
p-value (Lilliefors test)	0.16	0.30

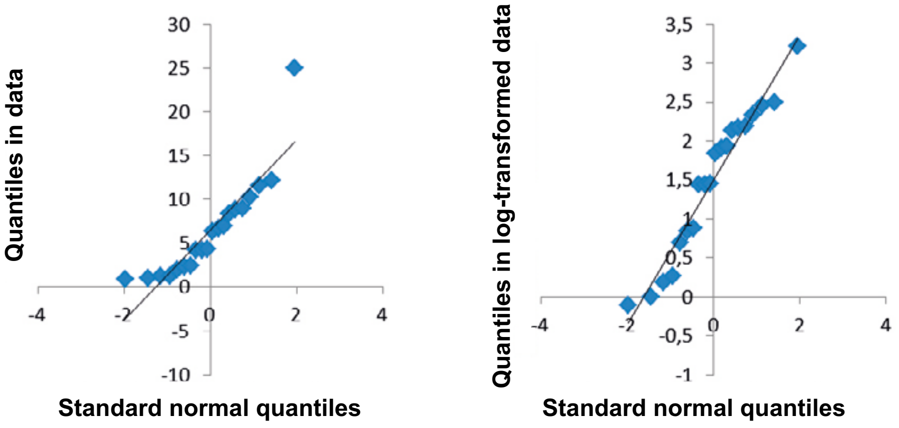


Figure E-3. Quantile plots with respect to normal and log-normal distribution for measured net count rate.

E3 Statistical analysis of clearance measurements

E3.1 Uncertainty in measured values

From the measured total and background count rate (ρ_T and ρ_B), the uncertainty in each individual measurement can be determined

$$s_{\rho_N}^2 = \frac{\rho_B}{t_B^2} + \frac{\rho_T}{t_T^2}$$

The standard deviation for the sum s_i in each individual measurement point can then be estimated according to

$$s_i^2 = (\gamma_D b)^2 s_{\rho_N}^2 + \left(\frac{\rho_N b}{n_\gamma}\right)^2 s_{\gamma_D}^2 + \left(\frac{\rho_N \gamma_D}{n_b}\right)^2 s_b^2$$

Where n_γ and n_b are the number of measurements in determination of γ_D and b. $s_{\gamma D}$ and s_b is taken from the estimated standard deviation in Table E-1 and Table E-4. Table E-4 presents the calculated sum, standard deviation and the upper limit for a confidence interval for the sum of measured values. The sum is below 1 in all measurement points, but in one case (no 12) the upper limit exceeds the condition for clearance. Remedial action should be considered for this measurement point and a study should be made of how measured count rates are distributed over the object, to see if there is a delineated area with elevated net count rate.

Table E-4. Calculated sum (*i*) for measured net count rate including assessment of uncertainty.

Measurement	Sum	s_i	i + 1 645s_i
1	0.33	0.03	0.38
2	0.46	0.04	0.51
3	0.32	0.02	0.35
4	0.03	0.01	0.05
5	0.16	0.01	0.18
6	0.05	0.01	0.06
7	0.39	0.03	0.44
8	0.05	0.01	0.06
9	0.09	0.01	0.10
10	0.16	0.01	0.18
11	0.25	0.02	0.28
12	0.94	0.10	1.10
13	0.16	0.01	0.18
14	0.34	0.03	0.38
15	0.09	0.01	0.11
16	0.26	0.02	0.29
17	0.08	0.01	0.09
18	0.24	0.02	0.27
19	0.44	0.03	0.49
20	0.04	0.01	0.05

E3.2 Activity level for the object

Based on determination of scintillation efficiency and clearance constant and measured net count rates, estimates of the mean value and standard deviation have been determined for all parameters that are needed for calculation of the sum. The uncertainty distribution (L) for the sum's mean value and the sum in conjunction with a new (hypothetical) measurement of net count rate can then be determined by simulation (Figure E-4 and Figure E-5). From the simulations, a 95 % limit for these parameters can be estimated (UCL95 and P95 in Table E-4) by calculating the value that is only exceeded by 5 % of the simulated values. An upper limit for these estimates can be determined by first calculating

$$p = 0{,}95 + 1{,}645 \cdot \sqrt{\frac{0{,}95 \cdot (1 - 0{,}95)}{10^6}} \approx 0{,}9504$$

and then finding the value that is only exceeded by (1–p) · 100 %) of all simulated values.

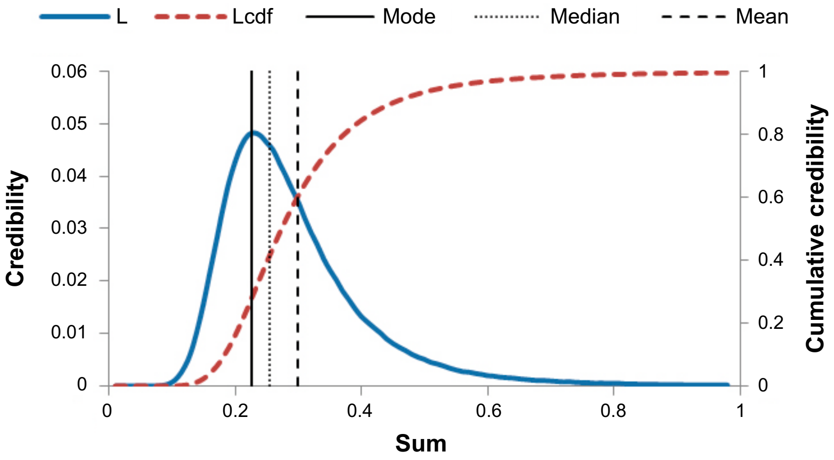


Figure E-4. *Uncertainty distribution (L) and cumulative uncertainty distribution (Lcdf) for the mean value of the sum. The distribution has been calculated by simulation (10^6 simulations).*

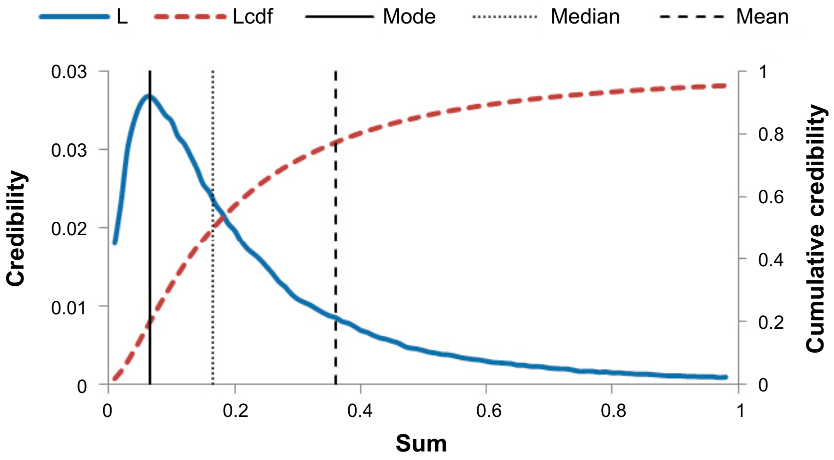


Figure E-5. *Uncertainty distribution (L) and cumulative uncertainty distribution (Lcdf) for the sum of a new (hypothetical) measurement of net count rate (10^6 simulations).*

From the simulation of a new measurement, it is also possible to calculate the percentile corresponding to the sum 1 (P(i=1) in Table E-4).

The results of the calculations show that the object can be cleared (despite slightly elevated net count rate in measurement point no. 12), since a new measurement of net count rate would most likely not result in a sum larger than 1 (see Section 8.1.2 in the main report).

Table E-5 . Calculated limit values for the sum's mean value and the sum for a new measurement of net count rate. The upper limit corresponds to the upper limit in a 95 % confidence interval for simulated data. P(i=1) is the percentile corresponding to sum = 1.

	Limit	Upper limit
UCL95	0.527	0.528
P95	0.938	0.941
P(i=1)	0.954	0.954

E3.3 Distribution of activity and occurrence of anomalies

The risk for occurrence of one or more points with elevated activity (anomaly) follows a beta distribution (beta (1.21)) for an object with 20 measured net count rates. This makes it possibly to say with 95 % safety that the probability of anomalies is less than 13 % and with 66 % credibility the probability is less than 5 %. By also considering the object's total area, risk category and any scanning (comprehensive) measurements from the radiological survey, it should be possible to argue for why this risk level is acceptable.

Clearance levels for the sorting plant in Ranstad

F1 The sorting plant in Ranstad – an illustrative example

In the Ranstad plant, uranium was leached from alum shale, during the years 1965–1968, with the purpose of supporting domestic nuclear fuel production for the Swedish nuclear power programme. During subsequent years other activities continued, including leaching of low- and intermediate-level waste from manufacturing of nuclear fuel. Ranstad is a nuclear facility and follows the regulations for these. The facility consists of a number of buildings and large quantities of objects, leaching residues, gravel, electrical components and combustible materials. Both clearance and conditional clearance needs to be applied to manage the various materials that arise during dismantling and demolition of the facility. Decommissioning of the facility is carried out in stages and here, decommissioning of the sorting plant has been chosen to illustrate a detailed example, since it was recently finished. The description is based on the dispersion and dose calculations (Kemakta 2012), which were a part of the application for conditional clearance.

Since there were different kinds of radioactive material, it was important to describe each material with respect to concentration and leachability for the most important radionuclides and their tendency to form dust. There was also different options for disposal of the radioactive material. The different disposal options were studied, including possible sites for final disposal. Thereafter, it was possible to evaluate different combinations of radioactive material and disposal option to determine the optimal solution. The evaluation was carried out based on calculations for the selected scenarios.

F2 Selection of scenarios

The selection of scenarios was made based on the scenarios presented in the literature (in particular IAEA 2005). For exposure to the public, a scenario with dispersion to a self-sufficient household was chosen. The exposure pathways included were: well or surface water recipient used as drinking water, surface water recipient used for fishing, land that is irrigated with water from a well or surface water recipient and land used for farming of crops. Humans ingest food in the form of self-produced root crops and vegetables, milk and meat and are exposed to the irrigated soil through dust and direct ingestion of soil. The cattle eats self-produced fodder and drinks water from the well or surface water recipient. Since this scenario includes many exposure pathways, it is deemed to be bounding for whether the obtained dose is acceptable.

In addition to this possible scenario, two scenarios for future intrusion was chosen, since also conditional clearance entails that knowledge of the presence of radioactive material on the site is not ensured. In one intrusion scenario it is assumed that someone settles on the site, and in the other it is assumed that construction workers are exposed during road construction on the site. For the scenario with residents at the landfill, external dose is considered, dose through dust and direct ingestion of soil as well as cultivation of root crops and vegetables in soil that has been contaminated through mixture with underlying radioactive material. For construction workers, external dose and dose through inhalation of dust are considered.

F3 Choice of input data

The choice of input data was made so that the values were as representative/realistic as possible, but nevertheless with reasonable caution. Table F-1 reviews all different types of input data with comments on how the selection of parameter values has been made.

Tabell F-1. Compilation of input data for Ranstad with comments on how they were selected.

Type of data	Comment on the choice of parameter values
Materials and radionuclides	**All scenarios** – Radionuclide-specific measurements were made on different types of radioactive material prior to dismantling. Based on the measurements, it was determined which radionuclides needed to be included in the calculations. The weight of materials of various types was determined. The radionuclide's gamma energy and internal dose factors were obtained from publicly available data. The dust was assumed to have the same concentration of radionuclides as the solid material.
External exposure	**The public** – Radionuclide concentration in soil is calculated through dispersion calculations. Exposure from contaminated soil is judged to occur most of the time spent outdoors. With regard to seasonal variations, the chosen exposure time is in average about seven hours per day. The geometry for exposure is an "infinite surface" (EC 1993). No external shielding was considered. **Residents** – Radionuclide concentration in soil is calculated for a dilution with topsoil, where the radioactive material comprise 3 % (EC 1999). Exposure time and exposure geometry are the same as for the self-sufficiency scenario for the public. **Construction workers** – The work with building a road through the area with radioactive material is expected to continue for 100 hours (IAEA 2003). The geometry for exposure was chosen as 1/3 of the exposure from an *infinite surface*. No external shielding was considered.
Internal exposure	**The public** – Radionuclide concentration in soil is calculated through dispersion calculations. Publicly available data are used for age-dependent inadvertent ingestion of soil, dust concentration in air and for age-dependent inhalation rates. The exposure time for inhalation of dust is assumed to be the same as the exposure time for external exposure, i.e. most of the time spent outdoors. **Residents** – Radionuclide concentration in soil is calculated for a dilution with topsoil, where the radioactive material comprise 3 % (EC 1999). Other data are the same as for the self-sufficiency scenario for the public. **Construction workers** – During the entire time of construction work, 100 hours, the dust concentration has been selected based on publicly available measurement data of the concentration in the cab in machines working in dusty environments.
Dispersion of radionuclides with water	**The public** – Leaching data were determined for important radionuclides on samples of different types of material. In addition to ordinary two stage batch tests, three stage batch tests and pH-stat tests were performed. Publicly available data were used for calculation of retardation in the groundwater zone, for example sorption data (K_d values). Site-specific data were used for surfaces with radioactive material, infiltration (reasonable assessment based on precipitation, properties of superimposed materials and vegetation), distance to the well and surface water recipient (reasonable assessment based on maps), hydraulic gradient (topography and measurements in groundwater pipes), hydraulic conductivity (material samples from the area), groundwater zone thickness (measurements/maps), porosity and density. Measurement data for the flow in the surface water recipient. **Residents** – Not included in this scenario. **Construction workers** – Not included in this scenario.
Dispersion in the food web	**The public** – Radionuclide concentration in the soil is calculated from assumed data on cultivated area, irrigation rate (irrigation with water from well/surface water containing radionuclides), cultivation depth, density, porosity, net precipitation, bioturbation[1], sorption data (K_d values). Net infiltration has been assessed based on site-specific information on precipitation, while other data have been chosen based on publicly available data. Publicly available data regarding transfer between for example water–animals, soil–fodder, fodder–meat/milk and water–fish. Publicly available data on animal consumption of water and fodder. Publicly available age-dependent data regarding normal Swedish consumption of water, root crops and vegetables, milk, meat and fish (for example Karlsson and Aquilonius 2001). **Residents** – Radionuclide concentration in soil is calculated for a dilution with topsoil, where the radioactive material comprise 3 % (EC 1999). Other data are the same as for the self-sufficiency scenario for the public. **Construction workers** – Not included in this scenario.

[1] Bioturbation is a collective name for fauna (animals) and flora (plants) mixing and transport of materials, fluids and gases.

F4 Uncertainty analysis

Parameter values for calculation of dispersion and exposure have been chosen in order not to underestimate the dose that may arise in the future. For different reasons, there are uncertainties in chosen assumptions and parameter values. In order to understand how they affect the calculated dose, a number of variation cases have been conducted where one or in some cases several parameter values have been changed. The variation cases give an understanding of the model's sensitivity to different assumptions and parameter values.

The variation cases studied the impact on dose consequence for altered parameter values regarding for example inventory, leaching rate, leached fraction, infiltration through demolition waste, transport distances and transport time and immobilisation at transport in the groundwater zone.

The calculations for the public shows that for all types of radioactive material, the maximum dose is dominated by Ra-226 and its progeny, the dominant exposure pathway is consumption of drinking water from a well and the most exposed age group is 12–17 years. For exposure through the nearest surface water recipient, the dose is dominated by Ra-226 with its progeny from ingestion of fish. The variation cases showed the greatest difference in the calculated doses for altered values of immobilisation and distance and transport time to the well.

The calculated dose at intrusion is dominated by Ra-226 with its progeny for both residents and construction workers. The dose for residents is dominated by the intake of root crops and vegetables cultivated at the site (80 % of the total dose). For construction workers, the contribution from external exposure is approximately 60 % and from inhalation of dust about 40 %.

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SKB is responsible for managing spent nuclear fuel and radioactive
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