Safety Reports Series

No. 77

Safety Assessment for Decommissioning

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SAFETY REPORTS SERIES No. 77

SAFETY ASSESSMENT FOR DECOMMISSIONING

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2013

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1400 Vienna, Austria
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tel.: +43 1 2600 22417
email: sales.publications@iaea.org
http://www.iaea.org/books

Printed by the IAEA in Austria
June 2013
STI/PUB/1604

IAEA Library Cataloguing in Publication Data

Safety assessment for decommissioning. — Vienna : International Atomic Energy Agency, 2013.
p. ; 24 cm. — (Safety reports series, ISSN 1020–6450 ; no. 77)
STI/PUB/1604
ISBN 978–92–0–141410–6
Includes bibliographical references.

1. Nuclear facilities — Decommissioning. 2. Radioactive substances — Safety measures. I. International Atomic Energy Agency. II. Series.

IAEAL 13–00825

FOREWORD

In the past few decades, international guidance has been developed on methods for assessing the safety of predisposal and disposal facilities for radioactive waste. More recently, it has been recognized that there is also a need for specific guidance on safety assessment in the context of decommissioning nuclear facilities. The importance of safety during decommissioning was highlighted at the International Conference on Safe Decommissioning for Nuclear Activities held in Berlin in 2002 and at the First Review Meeting of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management in 2003. At its June 2004 meeting, the Board of Governors of the IAEA approved the International Action Plan on Decommissioning of Nuclear Facilities (GOV/2004/40), which called on the IAEA to:

> "establish a forum for the sharing and exchange of national information and experience on the application of safety assessment in the context of decommissioning and provide a means to convey this information to other interested parties, also drawing on the work of other international organizations in this area".

In response, in November 2004, the IAEA launched the international project Evaluation and Demonstration of Safety for Decommissioning of Facilities Using Radioactive Material (DeSa) with the following objectives:

— To develop a harmonized approach to safety assessment and to define the elements of safety assessment for decommissioning, including the application of a graded approach;
— To investigate the practical applicability of the methodology and performance of safety assessments for the decommissioning of various types of facility through a selected number of test cases;
— To investigate approaches for the review of safety assessments for decommissioning activities and the development of a regulatory approach for reviewing safety assessments for decommissioning activities and as a basis for regulatory decision making;
— To provide a forum for exchange of experience in evaluation and demonstration of safety during decommissioning of various types of facility using radioactive material.

This book presents the outcomes of the work carried out in fulfilling the action plan through the DeSa project (November 2004–November 2007);

it contains a summary of the whole project and a methodology for the safety assessment of the decommissioning of facilities using radioactive material. It is supported by technical reports provided in the annexes.

The IAEA would like to express its gratitude to all of the experts who contributed to the development and review of the report, and in particular to the coordinating working group of the project: K. Percival (United Kingdom), Chairman; A. Joubert (South Africa); J. Kaulard (Germany); K. Lauridsen (Denmark); J.-G. Nokhamzon (France); R. Ferch (Canada); P. Manson (United Kingdom); and S. Thierfeldt (Germany). The IAEA officers responsible for this publication were B. Batandjieva and V. Ljubenov of the Division of Radiation, Transport and Waste Safety.

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INTRODUCTION AND OVERVIEW

The number of nuclear facilities and other facilities that use radioactive material that are in the process of being, or planned to be, shut down, either as they reach the end of their design lifetime, or earlier for safety or political and social reasons, has been increasing worldwide. This has led to an increase in the awareness of regulators and operators of the importance of developing safety requirements and criteria for decommissioning, and for demonstrating compliance with them.

The safety assessment of operational facilities in the nuclear industry is well understood, and methodologies have been developed and refined over several decades. In the area of radioactive waste management, safety assessment methodologies for near surface disposal facilities have been harmonized internationally over the last few years (e.g. through the IAEA's ISAM (Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities) and ASAM (Application of Safety Assessment Methodology for Near Surface Radioactive Waste Disposal Facilities) projects). There is, however, less widespread experience of safety assessment applied to the decommissioning of facilities among IAEA Member States and, consequently, there is less commonality of approach internationally.

The approach to safety assessment in decommissioning projects is recognized as differing in a number of important ways to that developed for operational facilities. This is because decommissioning involves the breach of containment and other engineered safety barriers that are fundamental to safety during the operational phase of a facility, and because facility conditions and configuration are subject to constant change during decommissioning. The safety assessment process for decommissioning provides a basis on which the safety of workers and the public can be ensured through the evaluation of the consequences of potential hazards and the identification of the ways that they can be mitigated, so that the associated residual risks are as low as reasonably achievable (ALARA).

A general requirement in decommissioning is the development of a decommissioning plan that includes, or has associated with it, an evaluation of the potential radiological consequences to the public and workers during planned decommissioning activities and as a result of any credible accidents that might occur during such activities. Various approaches have been used in performing decommissioning safety assessments, and there is a need to harmonize these approaches and to share good practice and lessons learned between countries, in particular, to share financial or human resources with countries with limited decommissioning experience.

In 2004, in response to the outcomes of the International Conference on Safe Decommissioning for Nuclear Activities: Assuring the Safe Termination of Practices Involving Radioactive Materials (Berlin, Germany, 2002), the IAEA initiated the International Action Plan on Decommissioning of Nuclear Facilities. As part of this action plan and in response to a number of requests for advice and inquiries from Member States, the international project Evaluation and Demonstration of Safety for Decommissioning of Facilities Using Radioactive Material (DeSa) was launched. Its main objectives were:

— To develop a harmonized approach to safety assessment and to define the elements of safety assessment for decommissioning, including the application of a graded approach;
— To investigate the practical applicability of the methodology and performance of safety assessments for the decommissioning of various types of facility through a selected number of test cases;
— To investigate approaches for the review of safety assessments for decommissioning activities and the development of a regulatory approach for reviewing safety assessments for decommissioning activities and as a basis for regulatory decision making;
— To provide a forum for exchange of experience in evaluation and demonstration of safety during decommissioning of various types of facility using radioactive material.

The DeSa project provided a forum for the exchange of lessons learned between site operators, regulators, safety assessors and other specialists involved in the development, implementation and review of safety assessments applied to the decommissioning of nuclear power plants, research reactors, nuclear laboratories, nuclear fuel cycle facilities, etc. The project was very well supported by Member States from the first joint DeSa meeting held in November 2004 through to the fourth and final meeting held in October 2007. Typically, 60 people, representing more than 30 Member States, attended these meetings.

The main outcomes of the DeSa project are presented in four main parts, which address the following key issues:

— Safety assessment methodology for decommissioning of facilities using radioactive material (main body of the book);
— Application of DeSa safety assessment methodology to test cases (Annex I, Parts A, B and C);

— Graded approach to safety assessment for decommissioning of facilities using radioactive material (Annex II);
— Regulatory review of safety assessment for decommissioning of facilities using radioactive material (Annex III).

The annexes[1] are on the attached CD-ROM.

SAFETY ASSESSMENT METHODOLOGY

On the basis of experience obtained on safety assessment in the context of decommissioning in Member States, the main features of the process are summarized, and recommendations on producing, reviewing and implementing safety assessments are made. The overall recommendations are presented in this report; they are supported by the specific recommendations contained in Annexes I–III.

Safety assessments are required to support the decommissioning plan and, therefore, need to be incorporated into the decommissioning plan or be contained in supporting documents. For larger projects consisting of a number of phases, it is usual practice for the detailed safety assessments to be separated from, but complementary to, the decommissioning plan. The decommissioning plan for such projects may, however, contain an overall or preliminary safety assessment.

Regardless of the way the safety assessment is documented, it should be performed in a systematic, logical and transparent manner with clear start and end points for each phase, and a clear end state for the decommissioning project as a whole.

There is rarely a single safety assessment for a decommissioning project, other than for the less complex projects (e.g. facilities using only sealed radioactive sources). For projects with a number of distinct phases, it is normal to produce a safety assessment for each phase as the project proceeds; this provides for flexibility as experience is gained as the project develops.

The decommissioning process follows the operational phase of a facility. It is normal for there to be a transition phase in which preparations for decommissioning take place, and these are also subject to safety assessment. The operational, transition and decommissioning phases of a facility have common characteristics and interdependencies (e.g. design and operational knowledge), as well as differences, such as the nature of the associated hazards to the public, workers and the environment.

[1] The annexes on the attached CD-ROM have been prepared from the original material as submitted for publication and have not been edited by the editorial staff of the IAEA.

In the DeSa project, an overview of the safety assessment process and its associated management and quality aspects was developed, and the various purposes of safety assessment were identified. The primary purpose is to identify hazards during normal and potential accident conditions, and then to identify engineered and administrative control measures to prevent, eliminate or mitigate the hazards and their consequences. As part of this process, it should be demonstrated that residual risks have been reduced to ALARA and to within nationally prescribed safety criteria. It is important to demonstrate to the regulatory body and to other interested parties that the safety of the planned decommissioning activities is in compliance with regulatory criteria.

Industrial and chemical hazards are generally more significant in decommissioning activities than radiological hazards. A general methodology for integrating the control of safety for all hazards is described in this report.

The main steps of the harmonized safety assessment methodology for decommissioning are presented in Fig. 1 and listed below:

— Safety assessment framework;
— Description of the facility and decommissioning activities;
— Hazard identification and screening;
— Hazard analysis;
— Engineering analysis;
— Evaluation of results and identification of safety control measures;
— Independent review by the operator and/or regulator prior to implementation of the controls in practice.

Figure 1 represents the core of the DeSa safety assessment methodology, but there is extensive scope for flexibility in the calculation and assessment methods used in each of the steps. A deterministic approach to safety assessment is promoted, as this allows the identification of safety control measures as layers of protection to afford defence in depth to a degree appropriate to the level of risk presented. However, the probabilistic approach can also be utilized in a complementary manner. The use of risk categorization methods is illustrated in the test cases of Annex I.

Various hazard identification techniques are specified; the choice of technique is influenced by the degree of complexity of the planned or ongoing decommissioning work. Hazard and accident grouping and screening techniques are discussed to enable the application of safety assessment to be optimized. The importance of defining the end point at each phase of the decommissioning project is also emphasized.

Once the hazards and initiating events for normal and accident scenarios that require evaluation have been identified, they can be assessed by a number of methods ranging from simple calculation methods to the use of approved computer codes. It is normal to quantify the radiological consequences that would result without safety control measures being in place, so that the degree of risk presented can be seen.

By means of this process, the requirements for controls can be determined. The controls are applied to ensure that radiological safety and risk criteria are complied with and that risks are reduced to ALARA. Advice on the selection of safety controls is presented, with engineered controls being preferred wherever practicable. The necessary engineering evaluation of such controls is addressed in detail and illustrated in the three test cases in Annex I. The outcome of a safety assessment may be sensitive to the assumptions and data used, and it is, therefore, important to explore the robustness of these before confirming the adequacy of the control measures identified from the safety assessment.

A graded approach is one in which the complexity and detail of the safety assessment are chosen to be appropriate to the level of hazard and consequent risk presented by the planned work. This approach is vital in order to provide safety assessments that are appropriate to the task and to avoid unnecessary effort and complexity. Member States' experience in applying a graded approach to the development and review of safety assessments for decommissioning was reviewed in the DeSa project. The subject is regarded as being important in decommissioning, and a separate annex (Annex II) is dedicated to the subject.

Experience has shown that confidence building and the involvement of interested parties are essential for the success of a decommissioning project. Recommendations have been developed on how to build the confidence of all relevant interested parties in the safety assessment (see main body of the book and Annex III). There are a number of aspects to this, the first being the establishment by the site operator of an effective and comprehensive safety management programme. This should include requirements for the safety assessment and engineering teams, ranging from their working procedures, calculation methodologies, data, source references, and the qualifications, training and experience of the team members. Another key aspect of confidence building is the requirement for independent review of safety assessment on behalf of the operator. This may be carried out within the operator's organization by competent person(s) independent of the decommissioning project team or by external experts/organizations. National practices vary and in some Member States, an internal authorization mechanism based on independent review is implemented with the agreement of the regulatory body. However, in general, the regulatory body reviews safety assessments and, while regulatory experience in the review of safety assessments exists, there is limited documented guidance on regulatory review in this context. Member States' experience was reviewed in the DeSa project, and a harmonized regulatory review procedure was developed (Annex III).

The updating and ongoing review of safety assessments is a feature of many decommissioning projects, especially those with long term schedules. If a decommissioning project has a number of distinct phases, safety assessments may be produced progressively throughout the project to accommodate and reflect up to date information on the facility. During this time, there may be changes to work methods or strategies if conditions are not as originally determined in the decommissioning plan and authorization. The control and updating of safety control measures as each phase is completed is an important facet of the review of safety assessment by the operator. In general, radiological hazards are diminished as a decommissioning project proceeds and as spent fuel and radioactive waste are removed. Thus, during the decommissioning project, the level of independent review is expected to be commensurately reduced, possibly with the regulatory body placing more reliance on internal reviews by the operator for the less hazardous phases of the work.

The use of safety assessment in the specification of control measures was one of the main topics addressed in the DeSa project. Recommendations on the general ways in which safety control measures and task based controls should be defined and utilized to ensure worker and public protection from industrial and hazardous substances are given in this report. Special attention is paid to bringing together and implementing these controls prior to the commencement of decommissioning work. This subject is emphasized throughout the report, noting that industrial risks to workers are generally greater than radiological risks during decommissioning work.

APPLICATION OF THE DeSa SAFETY ASSESSMENT METHODOLOGY TO TEST CASES

To demonstrate the application of the DeSa safety assessment methodology (see Fig. 1), three examples of facilities to be decommissioned were selected for evaluation:

— A nuclear power plant;
— A research reactor;
— A nuclear laboratory.

The facilities chosen cover a wide range, both in scale and associated hazard. The test cases are based on the decommissioning of real facilities, but the facilities are kept anonymous in the material presented, as decided by the project participants.

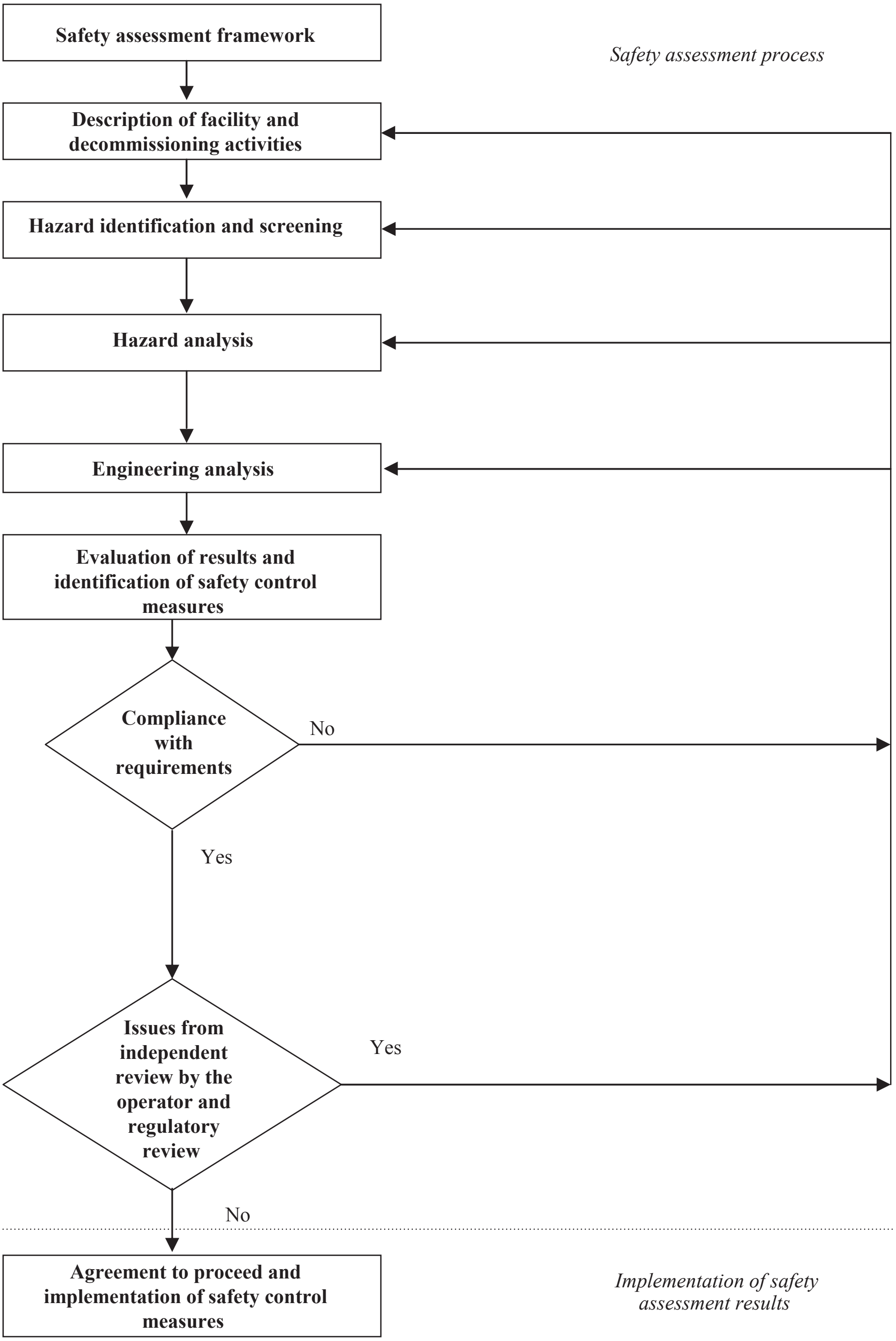

FIG. 1. Main steps of safety assessment.

The responsible operating organizations for the facilities agreed to provide all of the necessary technical information to allow safety assessments to be conducted. The test cases demonstrate that the DeSa safety assessment methodology has general applicability.

Once the safety assessments for the decommissioning of the nuclear power plant, the research reactor and the nuclear laboratory had been developed, each test case was reviewed at the draft stage by the regulatory review working group and the graded approach working group of the DeSa project to provide a simulation of a regulatory review and to demonstrate that the regulatory review procedure developed for DeSa (Annex III) and the recommendations on the graded approach (Annex II) are robust.

Each of the test cases is briefly discussed below and more fully addressed in Annex I. The three test cases are also analysed from the perspective of the graded approach and regulatory review in Annexes II and III, respectively.

Safety assessment for nuclear power plant decommissioning

The subject of this test case was a boiling water reactor that was used for electricity generation, but which had reached the end of its operating life. The reactor had been defuelled, and the fuel had been removed from the site where two of these units were located. A plan for the transition and preparatory phases for decommissioning was available, but the planned decommissioning work was at an early stage and had not been subjected to a detailed safety assessment. The purpose of the safety assessment for this unit was to support the decommissioning plan for immediate dismantling.

The safety assessment for a large nuclear power plant is broad in scope and results in a large amount of documentation. Owing to the time constraints on the DeSa project, it was not considered practicable to address the decommissioning of a whole nuclear power plant. It was, therefore, decided that by selecting two radiologically significant decommissioning tasks (dismantling of two systems), a satisfactory demonstration of the DeSa safety assessment methodology would be achieved and that it would be broadly representative of most decommissioning projects for light water reactors. The nuclear power plant test case, therefore, deals broadly with the whole decommissioning project and the supporting safety assessment, and specifically addresses two significant decommissioning tasks for the purposes of demonstrating the DeSa methodology.

The two tasks chosen for the nuclear power plant test case were the complete decommissioning of:

(a) A system used for shutdown reactor cooling;
(b) The containment building spray cooling system.

The safety assessment showed that the main radiological hazards associated with these activities arise from the direct exposure of workers to radiation and from the inhalation of radioactive aerosols produced in cutting and grinding operations.

The effective radiation doses associated with these two tasks were shown to be well within relevant safety criteria, and no significant off-site accident scenarios were identified.

It is important to note that the estimated radiation exposures were related only to the decommissioning of two systems of one boiling water reactor unit. In an actual decommissioning project, radiation doses to workers and the public from all decommissioning tasks would need to be taken into account when evaluating compliance with the relevant safety criteria.

Safety assessment for decommissioning a research reactor

The DeSa safety assessment methodology was also applied to a smaller scale facility — a research reactor that was shut down in 2001 for immediate dismantling. The research reactor was a homogeneous liquid fuelled and moderated reactor with a low thermal power. Its fuel was enriched ^{235}U in the form of uranyl sulphate. The reactor had been shut down and its fuel removed before the commencement of decommissioning.

The purpose of the safety assessment was to support the decommissioning plan and the licence application for decommissioning. The safety assessment also aimed to:

— Confirm the safety of workers and the public during the planned decommissioning activities;
— Identify the requisite safety control measures;
— Act as a basis for seeking regulatory approval to proceed.

The safety assessment showed that the radiological hazards that could arise from planned decommissioning activities were well within the nationally adopted safety criteria. A range of accident conditions was also assessed; the most hazardous scenario was the combustion of the entire graphite inventory and the associated release of radionuclides from surfaces. This was considered to be a very improbable event but even so, the estimated doses were comparatively small.

Safety assessment for a nuclear laboratory

This test case was a safety assessment during the decommissioning of a nuclear laboratory. The laboratory is part of a laboratory complex in which some rooms in the building would remain operational after completion of the decommissioning of the laboratory.

The end point for this test case was decontamination of the internal surfaces of five rooms of the laboratory complex to a level that allows free access. This was an example of an interim end point, ahead of the ultimate site end state (unrestricted release).

The aim of the laboratory test case was to:

- Demonstrate compliance with safety criteria for protection of workers and the public;
- Define safety controls to be implemented in the decommissioning project.

This test case involves a relatively small scale facility with a high radioactive inventory and alpha emitting radionuclides. A relatively simple risk consequence model was used; this proved to be a powerful tool for screening out low risk accident scenarios and for identifying control measures. The use of an engineering assessment tool to categorize safety related structure systems and components was also demonstrated.

The project involved the invasive decommissioning of gloveboxes within a temporary modular containment with a dedicated active ventilation system and with work being conducted in polyvinyl chloride suits served by a dedicated breathing air system. The scope of decommissioning covered five rooms containing Pu-contaminated gloveboxes, and also involved the isolation of services, such as active ventilation, that were to remain in service for the rest of the complex. While the gloveboxes had been decontaminated and fixatives had been used inside them, the potential inhalation or ingestion of Pu was the most significant hazard to workers.

Accident scenarios involving fires were found to be of potential radiological significance. The most radiologically significant scenario was due to the hydrogen deflagration of a 200 L drum. However, the maximum estimated dose to members of the public was low, and so no additional control measures were required to ensure compliance with dose criteria.

The laboratory test case clearly illustrated that a small scale facility can lead to a complex decommissioning project.

GRADED APPROACH TO SAFETY ASSESSMENT

A graded approach should be applied in the planning, conduct and termination of decommissioning. A graded approach in the context of safety assessment and review means that the level of detail and the complexity of approach, the level of documentation, and other aspects necessary to demonstrate compliance with relevant safety requirements and criteria are commensurate with the magnitude of the hazards that are presented by the planned and ongoing decommissioning work.

Many Member States implement a graded approach within their safety assessment and review processes and procedures. However, international guidance in this field is limited. In the DeSa project, the experience of operators, regulators and experts involved in a wide range of decommissioning projects was collected, with the objective of developing recommendations on the application of the graded approach in the performance of the safety assessment.

The safety categorization of facilities and decommissioning tasks should be based on risk or hazard potential. Procedures written for the different categories can prescribe the level of independent review, the degree of defence in depth required and the nature of the safety assessment approval required. A categorization system can also be usefully applied to engineered safety measures, so that engineering evaluation demonstrates functional capability and is proportionate to the claimed safety function of the engineered control.

A graded approach should be systematic and based on a framework supported by procedures and guidance. Therefore, four key steps were identified and discussed in some depth, and supported by Member States' examples:

(a) Step 1 requires the bounding requirements of the safety assessment to be identified;
(b) Step 2 requires that a preliminary safety assessment be conducted;
(c) Step 3 uses a graded approach in facility and system categorization;
(d) Step 4 is the application of grading in the actual safety assessment.

The three test cases of the DeSa project were reviewed by the graded approach working group, and comments were made to the test case working groups. The cross-comparison of the three test cases revealed that grading had been applied in many areas of the safety assessment of the nuclear power plant, research reactor and nuclear laboratory, according to the complexity of the facility, the decommissioning work and the scenarios to be analysed. Details of the outcomes of the review are presented in Annexes II and III.

REGULATORY REVIEW OF SAFETY ASSESSMENT

As decommissioning activities increase worldwide, regulatory bodies are required to review safety assessments submitted by operators in support of decommissioning plans. In order to assist the regulatory process and, in particular, the review of safety assessments in accordance with international safety standards and good international practice, the DeSa project reviewed Member States' experience in this field and developed the specific recommendations outlined in Annex III.

International safety requirements relevant to the decommissioning of nuclear and other facilities are summarized in Annex III. The ways in which these requirements are implemented varies among Member States. For example, in some Member States, the decommissioning plan is the principal document that is submitted to seek legal authorization to proceed, whereas in other States, the safety assessments for planned activities form the main basis on which agreement is given. A discussion of the links between the safety assessment and the decommissioning plan is provided, so that different national practices and their common elements can be better understood.

A step by step approach for the review of decommissioning safety assessments has been developed. For each step in this approach, guidance for reviewers is presented in the form of suggested review questions to aid reviewers in reaching conclusions as to the adequacy of the safety assessment. The questions are intended to help ensure that the safety assessment is complete, covers the scope of the decommissioning work, is technically accurate and is performed to an appropriate level of detail. The questions are not intended to comprise an exhaustive checklist. For any particular decommissioning activity, some of the suggested questions may not be relevant. Application of the review procedure should lead to a systematic evaluation of safety and of the adequacy of the engineered barriers and administrative safety control measures that have been identified as satisfying safety criteria, defence in depth requirements and the ALARA principle.

One of the key aspects of the design of the regulatory review procedure is that the review be undertaken in a structured, systematic and transparent manner, in accordance with the regulator's own written quality and project management procedures. Owing to the continuous changes that occur during decommissioning, it is important that the regulatory review procedures be flexible enough to adapt to the situation, for example, by being applied to only a small part of a larger multistage decommissioning process. The level of detail to which the review is taken should also be commensurate with the safety significance of the planned activities. It is important that the regulatory approval process provide an appropriate role for the operator's own internal management control system, rather than relying on a rigid process requiring approval by the regulatory body at every step.

The regulatory review procedure was applied to the three test cases described above. The review of the three test cases highlighted a number of general issues. One key lesson learned was the importance of clearly defining the boundaries of a project and its associated safety assessment, as well as the start and end points of the decommissioning activity to which the safety assessment applies. It was also found to be very important that adequate support be provided for assumptions made, particularly during the system description and preliminary screening parts of the safety assessment.

KEY LESSONS LEARNED AND CONCLUSIONS

Key lessons learned

There is an interest from a large number of Member States in establishing a harmonized methodology for the safety assessment of decommissioning activities. Some of the specific and key lessons learned through the DeSa project include the following:

— Using a standardized framework and a systematic step by step methodology in the production of safety assessments leads to improved consistency and a quality product. Assessment tools and techniques are available internationally to allow the effective use of the methodology. A common approach to safety assessment has been agreed that can be applied worldwide; it has the following steps: (i) establishment of assessment framework, (ii) description of the facility and decommissioning activities, (iii) hazard identification and screening, (iv) hazard analysis, (v) engineering analysis, (vi) evaluation of results and identification of safety control measures, and (vii) review of compliance with safety criteria.

— Decommissioning of large facilities may be conducted in a number of phases in accordance with the decommissioning plan. It is generally good practice to produce separate safety assessments for different phases, so that they are focused on current and near term activities and to avoid overly complex documentation that unnecessarily addresses tasks that may not be executed until years later. The decommissioning strategy and work methods may evolve through a decommissioning project, so it is important that supporting safety assessments be kept in line with such project developments.

— A deterministic approach to safety assessment and the identification of safety control measures are recommended as being effective in providing adequate protection for workers and the public during decommissioning activities. However, probabilistic approaches can also be applied in a complementary manner.

— A comprehensive approach to the identification of radiological and non-radiological hazards should be applied; in most decommissioning projects, non-radiological hazards will predominate.

— A graded approach is generally applied by operators and regulators on the basis of various criteria, although there is no internationally agreed common approach. It is important that the extent of the safety assessment and its review are commensurate with the safety significance of the decommissioning work. Many examples of good practice have been identified in the DeSa project; they include the classification of facilities and decommissioning tasks, accident sequences and engineered systems. In some cases, safety assessment can be performed by using simple approaches, for example, enveloping methods or scenarios, by which compliance with safety criteria can be demonstrated.
— Decommissioning involves changing facility states (i.e. from operation to decommissioning), including the removal of engineered safety barriers. It is important to have effective processes for the review and revision of safety control measures as decommissioning proceeds. This area may need further development at international level.
— The safety role of many engineered structures, systems and components (SSCs) during decommissioning will differ significantly from their role during the operational phase of a facility. Some will be retired, new ones may be added and the functional requirements of others will change. Once fuel is removed, their importance to safety will normally decrease. It is, therefore, important that the safety requirements for SSCs be identified and classified in terms of their safety significance, and that the extent of engineering assessment be commensurate with their importance to safety.
— There seems to be limited experience worldwide on standardized systematic procedures for the review of decommissioning safety assessments. Progress was made in the DeSa project to identify good practices, analyse lessons learned and develop a useful tool that can be used by regulators, experts or organizations performing independent reviews or assessments. The interaction between operators and regulators through the DeSa project has proved to be valuable in the development of a review procedure for safety assessment for decommissioning. Although the methodology was developed for the purposes of the regulatory review, it may also be applied in independent reviews.
— It is important to ensure appropriate consideration of radioactive waste management in the development of safety assessment for decommissioning. For this purpose, it is essential to establish clear boundaries and interfaces between waste management and decommissioning activities and the scope of the associated safety assessments.
— The application of the methodology to a wide range of facilities was successfully demonstrated by means of the test cases. They also illustrated the application of the graded approach, with the level of treatment depending

on the hazard potential and the complexity of the decommissioning work to be analysed, for example, characterization of facilities and sites, screening of hazards and use of mathematical models.

These and other lessons learned during the project and embedded within this publication consolidate the knowledge and experience from decommissioning in over thirty Member States.

Conclusions

In response to the International Action Plan on Decommissioning of Nuclear Facilities, the international DeSa project has provided a useful platform for the presentation and exchange of lessons learned in the development and review of safety assessments for decommissioning. The project provided a forum for exchange between operators, regulators and other professionals involved in the planning, conduct and termination of a wide range of facilities, as well as a useful interaction with international bodies and committees, such as the Western European Nuclear Regulators' Association.

The project has led to the development of a harmonized safety assessment methodology, a regulatory review procedure and recommendations on the application of the graded approach. An important aspect of the DeSa work was the interfacing and coordination achieved with other IAEA projects such as the Safety Assessment Driven Waste Management Solutions project.

The project has aided the implementation of national decommissioning projects, the development of relevant international safety standards and has supported the provision of technical assistance to IAEA Member States in the area of decommissioning.

FURTHER AREAS OF DEVELOPMENT

It became apparent during discussions at DeSa project meetings that there is still a need for international guidance on some aspects of safety assessment, in particular, the role of safety assessments during the whole decommissioning life cycle. This is because a facility decommissioning project, unlike an operational facility, is subject to continuous change. This means that a variety of safety assessments is required to cover the lifetime of a facility. This includes preliminary assessments to support the preliminary decommissioning plan and those to support site closure and/or release from regulatory control.

1. INTRODUCTION

1.1. BACKGROUND

For facilities[2], decommissioning is the final phase in the life cycle after siting, design, construction, commissioning and operation. It is a complex process involving operations such as detailed surveys, decontamination and dismantling of equipment and facilities, demolition of buildings and structures, and the management of the resulting radioactive and other hazardous waste and materials, while taking into account the need to provide for the health and safety of workers and the general public, and protection of the environment.

Many different types of facility require decommissioning. They include nuclear power plants, research reactors, nuclear fuel cycle facilities, research laboratories and industrial facilities. In particular, an increasing number of research and nuclear power reactors will be closing down in the next few decades. The number of nuclear power plants worldwide exceeds 500 units, with more than 400 of them currently in operation [1]. In addition, over 500 research reactor and critical assembly units exist that will eventually require decommissioning [1]. A systematic approach is required for the demonstration of compliance with safety requirements and standards during all of the activities associated with decommissioning and the release of materials, buildings and sites from regulatory control.

Planning for decommissioning starts during the initial design of the facility and ends with the approval for final release of the facility by the regulatory body. During this time, a number of documents must be prepared to help ensure that the decommissioning process is carried out in a safe and efficient manner. The central document is the decommissioning plan [2–6]. One of the key components of the decommissioning plan is a safety assessment of the decommissioning activities, although for more complex decommissioning projects, the safety assessment may be presented separately. Although decommissioning has to be considered at the design stage and throughout the operational life of a facility [2–6], an updated or new safety assessment is required prior to the start of decommissioning.

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[2] ‘Facilities’ include nuclear facilities, irradiation installations, mining and milling facilities, waste management facilities and any other place where radioactive materials are produced, processed, used, handled, stored or disposed of — or where radiation generators are installed on such a scale that consideration of protection and safety is required.

Safety assessment[3] can contribute directly to safety by identifying potential hazards and appropriate mitigatory measures that can be put in place to protect workers, the public and the environment. Safety assessments are used to show that facilities will comply or continue to comply with established safety principles, standards and licence conditions.

Decommissioning operations may result in the removal of existing barriers, components or systems important to safety and in significant deviations from the safety procedures used during operation. They may include activities such as decontamination[4], the dismantling of components, and the cutting and handling of large pieces of equipment. As these actions have the potential to create hazards, safety assessment has an important role in helping to justify the selection of particular decommissioning strategies and in ensuring the safety of ongoing decommissioning operations.

1.2. OBJECTIVE

The objective of this report is to present a systematic methodology for the evaluation and demonstration of safety during decommissioning. The methodology is intended to assist operators and technical support specialists in planning and undertaking decommissioning activities for all types of facility. Approaches to the regulatory review of decommissioning safety are also addressed, and, thus, the report is expected to be of use to regulators. The report may also be useful to policy makers and to other organizations concerned with the safety of decommissioning. It complements the requirements and guidance on safety assessment for decommissioning established in the IAEA's Safety Standards Series publications [3, 8].

1.3. SCOPE

In this report, the term 'decommissioning' refers to administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility [3], with adequate regard for the health and safety of workers and members of the public, and for protection of the environment.

This publication addresses the approach for evaluating the radiological impact on workers, the public and the environment of normal anticipated decommissioning activities and from unplanned events and accidents that

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[3] 'Safety assessment' means the assessment of all aspects of the siting, design and operation of an authorized facility that are relevant to protection and safety.

[4] 'Decontamination' means the complete or partial removal of contamination by a deliberate physical, chemical or biological process [7].

might occur during decommissioning activities. All types of civilian facilities (e.g. nuclear power plants, research reactors, nuclear fuel cycle facilities, research laboratories, industrial plants, uranium mills and processing facilities, and medical facilities) are covered. Attention is given to the application of the methodology during the different phases of planning and implementation of a decommissioning strategy, up to the final release of the site from regulatory control. On-site radioactive waste management associated with decommissioning, including processing, storage and on-site handling, is also considered.

In cases where preparatory activities (such as the removal of spent fuel, other post-operational cleanup activities, or, in some cases, the initial remediation of post-accident situations in order to permit orderly decommissioning) are included in the decommissioning plan, the methodology of this report is also applicable. The methodology can be applied to safety assessments in the individual phases of larger decommissioning projects[5]. However, closure of radioactive waste disposal facilities and mine/mill tailing sites are outside the scope of the report. In the case of the entombment (in situ disposal) option for decommissioning of facilities, the methodology for safety assessment of the post-decommissioning end state would normally be based on the methodologies previously developed for the evaluation of the long term safety of near surface disposal facilities [9].

1.4. STRUCTURE

The book is structured as follows: Section 2 contains an overview of the safety assessment process and its management aspects. In Section 3, there is a step by step description of the safety assessment approach. The application of the graded approach is discussed in Section 4. In Section 5, there is a discussion of confidence building associated with the safety assessment. In Section 6, a review and update of safety assessments during the decommissioning process are described. In Section 7, a link between the safety assessment results and the development of the work control process and task analysis is described. Section 8 contains a summary of the report. The appendices describe and illustrate, by means of examples, the application of the methodology to a number of projects. The publication includes three annexes that contain technical reports related to: application of the DeSa methodology to test cases (Annex I); graded approach

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[5] The term ‘decommissioning project’ (or just ‘project’) is used throughout this report. The term is intended to mean all physical and administrative activities necessary to complete a defined scope of decommissioning work assigned to a management unit. This may cover a whole facility or part of one, and covers all necessary work such as planning, safety assessment and invasive decommissioning work.

to safety assessment (Annex II); and regulatory review of safety assessment (Annex III). The annexes of the report are on the attached CD-ROM.

2. SAFETY ASSESSMENT OVERVIEW

This section provides an overview of the main aspects of planning, development and review of safety assessments to support planned decommissioning activities. Safety assessment should be incorporated into the decommissioning plan or be part of supporting documents presenting the safety arguments; the actual arrangements may depend on the complexity of the project. For larger projects consisting of a number of phases, it is usual practice for the safety assessment to be separate from, but complementary to, the decommissioning plan.

Regardless of the way the safety assessment is documented, it should be performed in a systematic, logical and transparent manner with clear start and end points. The key elements of a safety assessment methodology are discussed in this section, and the actual steps in the execution of safety assessments are discussed in Section 3.

Decommissioning follows the operational phase and the subsequent transition activities in preparation for decommissioning. The life cycle phases of a facility have significant common characteristics and interdependencies (e.g. design, operational knowledge), as well as differences, such as the types and nature of the associated hazards to the public and workers, as presented in Table 1.

Owing to the complexity and variety of the activities during the decommissioning process, a graded approach is applied to the evaluation of safety during decommissioning, with technical resources being allocated in proportion to the risks presented by the planned decommissioning activities.

The transition between a facility's operational phase and decommissioning needs to be carefully managed in order to make good use of the site operator's knowledge and resources. Before a decommissioning plan and safety assessment(s) are developed and documented, it is good practice to review the facility instructions and facility surveillance programme for the operating phase, as a significant part of the operational phase work content can probably be dispensed with. It is important to carry out this review in a controlled manner and in accordance with the appropriate approval route for changes to safety case documentation.

TABLE 1. MAIN FACILITY CHARACTERISTICS DURING OPERATION AND DECOMMISSIONING

	Operation	Decommissioning
Hazard profile	Stable; well characterized; radiological hazards dominant; potential (inventory) for significant off-site effects; well known working environment	Frequently changing; often not well characterized; industrial safety issues become more dominant as the radiological hazard is decreased; off-site effects due to removal of inventory; changeable working environment
Work control and planning	Frequently performing routine tasks; focused on operation and maintenance; relatively short term tasks	Task or job oriented; new, first of a kind tasks; work planning for work-place safety critical
Hazard analysis	Operation oriented; generally stable	Dynamic; mainly task oriented; changeable
Workforce experience	Familiar with facility operation and routine work according to approved design	New missions; limited experience; subcontractors may not have process knowledge of facility operations; knowledge may need to be maintained for long periods
Contract management	Licensee managed and operated	Often short term contractor involvement; high level of dependence on contractor's performance; need for strong project management
Staff	Permanent and/or task oriented	Changeable according to the decommissioning tasks and phases
Reliance on permanent structures	Constant with regular maintenance	Interim facilities and degradation of structures
Regulatory oversight	Routine inspections; amendments to licence	Focused inspections; rapid approvals often required
Stakeholders	Routine communication with stakeholders	Dynamic and changing set of stakeholders (e.g. contractors, public)

2.1. OBJECTIVES OF SAFETY ASSESSMENT

Prior to the authorization for the decommissioning of a facility being granted, a documented assessment of the safety of decommissioning activities is generally required by the regulatory body. The safety assessment (sometimes referred to as a safety analysis) report can have a number of purposes:

- To support the justification for the selection of a decommissioning strategy;
- To provide a systematic evaluation of the safety consequences of both planned decommissioning operations and of potential accident scenarios;
- To provide documented evidence that the proposed decommissioning activities can be carried out safely and meet regulatory requirements for the protection of workers and members of the public;
- To provide a basis against which the safety of the proposed activities can be assessed by the regulatory body or by any other organization that is independent of the decommissioning project team;
- To document safety assessment results that can be used by the regulatory body and/or operator, as appropriate, to give formal approval to the proposed decommissioning activities;
- To identify the limits, controls and conditions for safe working to be applied to decommissioning activities to ensure that the requisite safety standards are met and maintained. In this report, they are referred to as 'procedural and engineered safety control measures'.

The safety control measures are one of the principal outputs from the safety assessment. Systems and components identified in the safety assessment as having a safety role should be included in the facility surveillance programme, which includes maintenance, inspection and testing requirements. Such safety related systems and components are referred to in this report as SSCs. The other main safety assessment outputs are procedural safety control measures, which should be built into the work procedures and associated documentation for the decommissioning operations. In some countries, there is a hierarchy within the safety control measures to highlight those of greater safety significance.

2.2. SAFETY ASSESSMENT AS PART OF DECOMMISSIONING PLANNING

A decommissioning project includes: project definition, scope of work, a management programme, safety assessment, management of radioactive waste, environmental impact assessment and any required regulatory approval.

A general characteristic of a decommissioning project is that the facility states change progressively as work proceeds (see Table 1). For this reason, it is important that the start and end points of the decommissioning phase or stage or project as a whole are clearly defined. In the decommissioning plan, this is achieved by having clear definitions of topics and issues such as the decommissioning strategy (immediate dismantling, deferred dismantling or entombment), interactions with other facilities at the site, sequencing of decommissioning tasks, and the scope of work at each decommissioning phase or stage.

Guidance on the contents of decommissioning plans can be found in several publications [3–6, 8, 10], and may include such items as a description of the facility, the decommissioning strategy, the regulatory requirements, the proposed decommissioning activities, information on the availability of services and decommissioning techniques, waste management arrangements, cost estimates, the safety assessment, the surveillance and maintenance programme, the environmental impact assessment, the compliance and environmental monitoring programme, the health and safety programme, quality assurance provisions, emergency planning arrangements, physical security and safeguards arrangements, and a final estimated inventory of residual contamination. Appendix I contains a suggested table of contents for a decommissioning plan, based on the references cited above. Some of the elements of this list may not be required for less complex and less potentially hazardous decommissioning projects.

A safety assessment is a necessary and integral part of the overall decommissioning plan. The safety assessment facilitates the planning of work in a progressive manner aligned to the needs of the project, and it indicates the required steps in hazard reduction. The results of the safety assessment are important for decommissioning planning (e.g. the establishment of safety measures, training programmes, surveillance and maintenance programmes, compliance and environmental monitoring programmes, health and safety programmes, and emergency planning) [11]. The decommissioning plan and the safety assessment must, therefore, be prepared together, as neither can be completed without the other.

The core membership of a decommissioning project team should include technical support staff, including a safety assessment member. This ensures that the safety assessor is provided with a clearly defined specification of the planned work, has a sound understanding of project strategy and objectives, and is in a position to influence evolving project strategy. When the development of the safety assessment is planned as an integral part of the work of the decommissioning project team, the safety assessment is much more likely to be fit for purpose, to be closely aligned to the planned decommissioning, to result in the minimization of delays and to achieve a high level of stakeholder confidence.

2.3. STAGED APPROACH TO SAFETY ASSESSMENT

For small scale projects (e.g. laboratories), the entire decommissioning safety assessment can be documented in a single report supported by key reference documents. It has been found, however, that for larger projects (e.g. nuclear power plants, fuel reprocessing plants), in which there may be a number of discrete phases and stages, and that may have a duration of several years, a phased approach to the development of safety assessment has considerable advantages in terms of programming, cost and quality (see Appendix II). A staged approach may require that the safety assessment comprise several separate reports, with the level of detail of the safety assessments for later stages typically being less than for the earlier ones.

The reasons for a staged approach being considered are various, but can include the following:

- Recognition that decommissioning is a process with successive stages, unlike the operational phase of a facility (see Table 1). Decommissioning can be characterized as a series of intrusive facility modifications justified by safety assessments to support each discrete stage of work (see Appendix III).
- Each invasive action has to be justified progressively depending on the circumstances, and this could modify successive work plans and safety arguments.
- A staged approach allows progress to be made in situations where facility information and inventory may be incomplete at the beginning of decommissioning. For example, uncertainty with regard to radioactive inventory and the condition of the facility may be reduced as progress is made with the decommissioning.

For the above reasons, in some circumstances, an initial safety assessment of the whole project may be desirable (see Appendix II). This will provide a demonstration that common engineered barriers such as containment, active ventilation, cranes and services are fit for purpose, as these are likely to be required in all stages of the decommissioning programme. It will also support the initial post-shutdown and decommissioning preparatory stages. This initial overall safety assessment can also be a strategic document setting out the logic and justification for the remainder of safety assessment development.

Since a decommissioning project is made up of a progressive sequence of activities, the required safety control measures for safe operations will evolve at each decommissioning phase/stage due to the elimination/reduction of hazards, the removal of engineered barriers and the different work being undertaken at each stage.

2.4. GRADED APPROACH TO SAFETY ASSESSMENT

At each type of facility, there will be hazards related to the decommissioning activities and also the potential for incidents and accidents. It is important that appropriate weight is given to activities and events with potentially higher associated risk in the safety assessment. Those without significant associated consequences should be identified, so that less analytical effort is expended on them. In general, the risk[6] to the public in the decommissioning phase will be significantly less than in the operational phase, as the mechanisms that could cause the discharge of radioactive material to the environment or direct radiation exposure are generally fewer.

As decommissioning proceeds, the off-site hazard potential from a facility will normally be reduced progressively as radioactive material and any irradiated fuel (for reactor facilities and reprocessing plants) are removed and converted or stored in a passively safe form. When a facility reaches a state where the remaining radioactive material is essentially residual contamination and activation products (e.g. for reactor facilities and accelerators), the main measures for risk mitigation will be for the purpose of protecting workers. In general, the main sources of radiation exposure to the general public are releases of radionuclides via gaseous and liquid discharges from normal dismantling operations or from accidents such as fires or loss of containment.

Considerable savings in safety analysis and assessment resources can be realized by adopting a graded approach to safety assessments, as outlined below and described in more detail in Section 4. A detailed assessment of this subject is presented in Annex II. The concept of the graded approach can be used to optimize the number and depth of safety assessments, providing a balance between cost and effort spent on the development and review of safety assessments. A graded approach also allows for greater focus to be put on the more significant issues and scenarios [12].

2.4.1. Adjusting safety assessment to overall risk level

Aspects of the safety assessment where grading may be used include the following:

— The overall level of detail of the analyses. Preliminary studies concerning the evaluation of consequences and estimates of radiation doses should be

[6] 'Risk' means the probability of a specified health effect occurring in a person or group as a result of exposure to radiation or other hazard [7].

carried out. If compliance with the relevant criterion (e.g. dose constraint for workers and for members of the general public) were readily demonstrated, no further assessment would be required. If not, a more detailed safety assessment would be required.

— The radiological characterization of the facility. The extent and detail of the characterization of the radioactive content of the facility should be influenced by the expected risk level, concerning, for example, the measurement of dose rates, determination of the contamination levels, determination of activation in reactor facilities, the use of scaling factors between key radionuclides and hard to detect radionuclides in the contamination, the density of sampling and other aspects.
— The safety assessment method that is used. A simple screening method may be used for cases where the associated risks are low. For cases in which there may be higher potential risks (e.g. nuclear power plants, large fuel cycle facilities), a detailed safety assessment, possibly using probabilistic methods, may be more appropriate.
— The degree of review and approval requirements. The nature and extent of the review and approval process, both within the operator's organization prior to submission, and if required by the regulatory body, should be in proportion to the assessed radiological consequences or level of risk.

The grading of the approach adopted may depend on a number of factors:

(a) Group 1 factors:
  (i) The purpose of the type of safety assessment being produced (preliminary or final decommissioning plan, stage of the decommissioning project);
  (ii) The presence and type of initiating events for incident/accident sequences (chemicals, high pressure, temperature, fire hazards, etc.);
  (iii) Likelihood and consequences of the hazards.
(b) Group 2 factors:
  (i) Site characteristics (seismic risks, flooding, influence from a neighbouring facility);
  (ii) The size and type of the facility (including its complexity);
  (iii) The activity inventory of the facility (including short or long lived radionuclides, presence of alpha emitting radionuclides, the chemical and physical state of the radioactive material);
  (iv) The quality of the radiological characterization of the facility;
  (v) The reliability of information and the availability of input data concerning the facility.

(c) Group 3 factors:
   (i) The state of the facility at the start of the decommissioning work (shutdown after normal operation, or shutdown after an accident; longer period of poor maintenance; uncertainty on the state of the facility);
   (ii) Changes to the controlled area (reduction or enlargement) during the progress of decommissioning work;
   (iii) The dose evaluation or hazard potential related to the decommissioning task to be carried out (in some countries referred to as a ‘safety category’);
   (iv) The end state of the decommissioning project (e.g. unrestricted or restricted use of the facility and/or the site);
   (v) Availability of applicable safety assessment results for similar cases.

In addition, the safety assessments pertaining to the decommissioning of nuclear facilities that have been shut down after an accident (e.g. Bohunice A1 or Windscale Pile 2) will usually be more complex than for installations that have undergone a regular shutdown. Further examples are presented in Appendices IV and V.

2.4.2. Graded approach in related fields

A graded approach can be used in many other areas of the decommissioning process. A report by the United States Department of Energy [13] indicates the following areas in which a graded approach may be useful:

— Work and process control;
— Documentation;
— Training;
— Oversight, i.e. surveillance, inspection and control;
— Organizational structure.

Figure 2, which is adapted from Ref. [14], illustrates the graded approach in these areas.

It is common practice in decommissioning projects to produce a detailed work breakdown structure (WBS) for programme control and cost control of projects. It is also a useful tool for planning safety assessments, particularly at a preliminary stage, as it illustrates planned work activities and is an aid in planning the application of a graded approach. An example of a WBS for a Romanian research reactor is shown in Appendix VI.

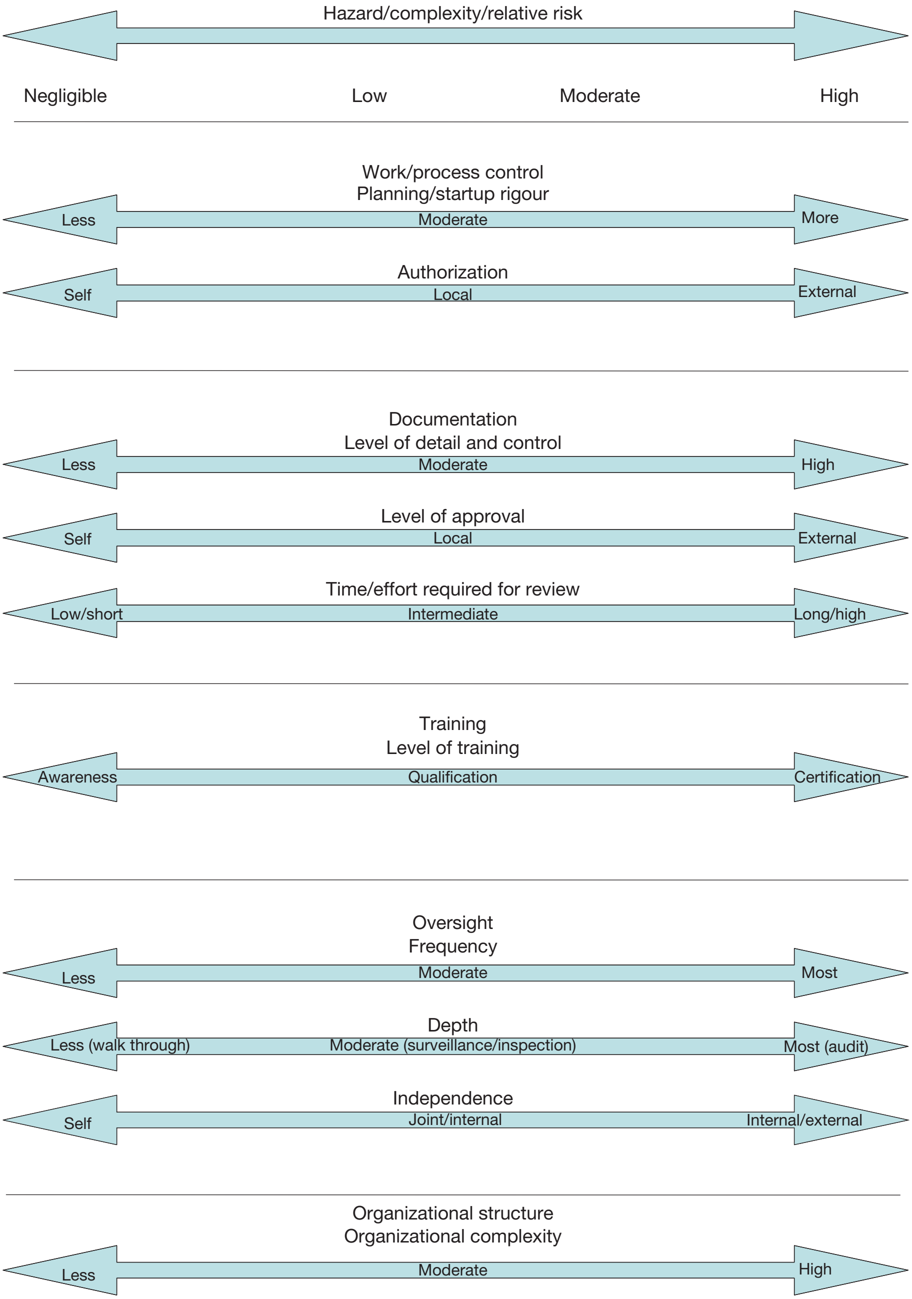


FIG. 2. Illustration of the graded approach in different aspects of decommissioning (adapted from Ref. [14]).

2.5. INTEGRATION ASSESSMENT OF RADIATION, CHEMICAL AND INDUSTRIAL HAZARDS

The radiation exposure of workers and the public associated with a decommissioning project can be categorized as external and internal. The main potential routes of exposure are: exposure to direct radiation sources (external) and inhalation and ingestion of radioactive material resulting from controlled discharges or due to a loss of containment and the release of particulate or liquids (internal). The radioactive contamination of wounds caused during cutting operations can be a significant mechanism for worker internal exposure. A criticality excursion can present a risk to both workers and nearby members of the public. Fires causing the release of airborne activity are another potential initiating event for off-site radiation exposure. These releases could arise due to fires within facilities or fires involving the on-site handling of radioactive material.

Safety assessment is directed primarily at analysing those pathways and event sequences that have a potential for causing significant off-site radiation doses to the public or to workers on-site. The assessment of these event sequences and the engineering and procedural controls that may be put into place to mitigate their impacts are then documented in the safety assessment as part of the overall set of safety arguments.

The management of contaminated land is a consideration on many legacy sites, and the potential for significant radiation exposure due to this contamination has to be assessed. The potential leakage of radioactive contaminants into the water table is a concern, mainly because of the hazard to humans as a result of consumption of contaminated drinking water and possibly also of foodstuffs obtained from areas in which contaminated irrigation water has been used.

Toxic and other dangerous chemicals must also be considered in the safety assessment if they represent a safety issue during decommissioning. Many legacy sites contain old chemical processing plants, and these can represent a significant source of risk during post-operational cleanup and decommissioning. Dangerous chemicals may also be used for decontamination purposes.

The most significant risk to workers on decommissioning sites will normally arise from the industrial hazards that exist on sites where building and demolition work is taking place. These hazards must also be considered in the safety assessment. The safety management programme at a facility should control physical work, so as to mitigate the effects of radiological, chemical and industrial hazards.

A key requirement of the safety measures or safety management programme is for the hazards associated with planned tasks to be assessed during the development of procedures and task specific instructions, both for routine tasks within a decommissioning project and for tasks performed once only, in order to identify any necessary controls. This may be achieved by providing a description of the scope of the planned tasks. This description is then used to perform a hazard assessment to identify potential hazards. Finally, the control measures necessary to reduce the risk from the identified hazards to an acceptable level are determined.

It is important to recognize that the safety control measures arising from a facility's safety assessment and those that arise from the assessment of the industrial hazards present during the execution of decommissioning tasks are complementary.

The controls arising from the task level safety assessment are designed to ensure that individual work packages (WPs) can be conducted safely. Controls such as respiratory protection, the use of safety harnesses, the isolation of live systems and personal protective equipment (PPE) are typically specified. Many parts of an operator's safety management programme are designed to implement health and safety legislation on matters such as lifting integrity, working with hazardous chemicals and working at heights. The derivation of safety controls from the safety assessment and from the safety management programme is illustrated schematically in Fig. 3.

Where chemical or other hazardous substances may represent a significant hazard to workers or the public, there may be national legal requirements for their control. An example is the United Kingdom's regulations on the control of substances hazardous to health (COSHH Regulations) [15].

2.6. SAFETY ASSESSMENT TECHNICAL TEAM

The safety assessment for decommissioning should be carried out by an experienced multidisciplinary team. The team composition will vary depending on the type and nature of the safety assessment it is to perform as a subproject of the decommissioning plan. For small facilities, and particularly for low hazard activities (e.g. decommissioning of a small research laboratory), it may be sufficient that a small team of safety analysts (or in some cases, even a single safety analyst) perform a safety assessment for decommissioning. For larger, more complex and safety significant facilities, such as nuclear power plants, a team of specialists is necessary for the development of the safety assessment. This team would be led and coordinated by a safety assessor, and would typically involve team members with knowledge in the following main areas:

- Engineering, facility design, systems and components;
- Radiation protection;
- Operational knowledge and history of the facility;

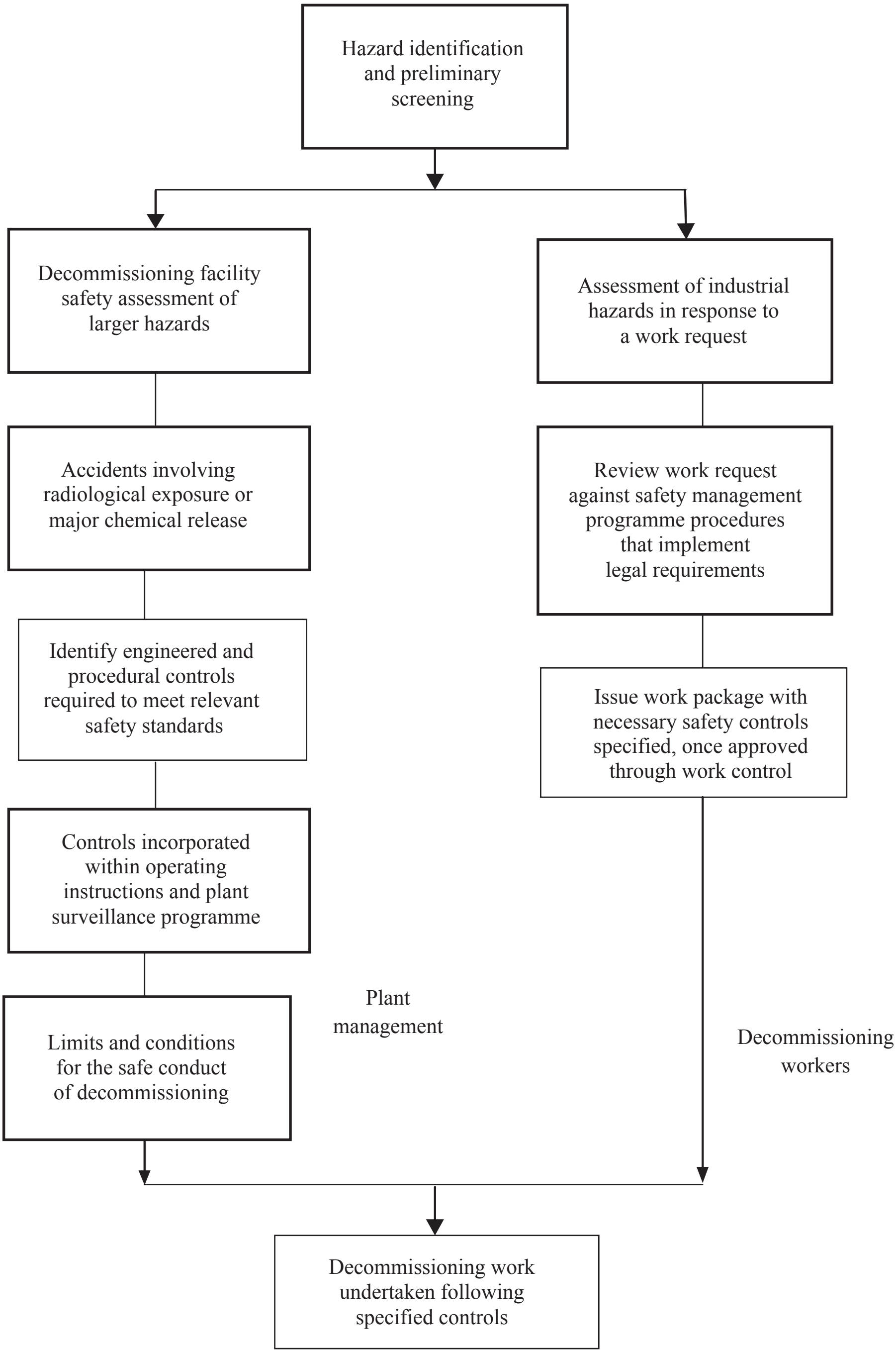


FIG. 3. Identification of safety control measures and the work control process.

— Industrial safety;
— Safety assessment;
— Specialist subjects as appropriate and necessary (e.g. criticality safety, hydrogeology, human factors, computer modelling);
— Radioactive waste management.

Reviewers of the safety assessment, including the regulatory body and other stakeholders, should be involved at the early phases of analysis, where possible.

2.7. DOCUMENTATION OF SAFETY ASSESSMENTS

The preceding sections have outlined the documentation required — from the plan setting out decommissioning strategy to the detailed task level hazard assessments.

The attributes that make a good safety assessment are summarized here in terms of nine overall qualities. The other sections of this report discuss many of these qualities in more detail, but they can be summarized as follows:

(a) Complete: All relevant threats to safety and their corresponding protection measures should be identified.
(b) Clear: The key points in terms of both strengths and weaknesses should be highlighted. The basis of all assumptions, conclusions and recommendations should be given and any unresolved issues explained and justified.
(c) Rational: Convincing, consistent and logical arguments to support the conclusions should be given.
(d) Accurate: The current state of the facility, equipment, processes and procedures should be accurately reflected.
(e) Objective: Arguments should be supported with factual evidence. Any use of inferred or extrapolated information should be substantiated, followed by a clarification of the nature and uncertainty of the assumptions. The adequacy of operational procedures, managerial controls and resources should be demonstrated by task analysis to an appropriate level.
(f) Appropriate: Analytical methods used to substantiate safety, together with computer code assessments, should be shown to be fit for purpose with adequate verification and validation.
(g) Integrated: The safety analysis, the engineering substantiation, operational requirements, dependency on external facilities/services should be integrated, and any associated assumptions that are being made clearly specified and substantiated.
(h) Current: It must be reviewed, revised and updated to ensure it remains current, for example, if the facility undergoes a significant modification or

a series of minor modifications that have a significant cumulative effect on safety.

(i) Forward looking: It should demonstrate that the facility will remain safe throughout a defined lifetime.

The documentation of the safety assessment normally has the following content:

(a) Introduction: This describes the scope of the work, making reference to the decommissioning plan, and clearly indicating any interim end states that the safety assessment covers.
(b) Summary of the safety assessment: A concise executive summary is invaluable for large safety assessment documents, and can act as a route map of the document's contents.
(c) Assessment framework: Provides a summary of the legal basis, safety requirements and criteria [16–18], time frames and decommissioning objectives such as interim project end points.
(d) Facility description and decommissioning activities: Provides a technical description of the facility and the decommissioning activities in sufficient detail to enable the safety assessment and engineering evaluation to be performed. This includes details of the inventory of hazardous materials and of safety related SSCs. The facility description may already exist in other documents that have been produced for the decommissioning project. The facility description contained in the operational safety assessment should be reviewed and, if appropriate, utilized.
(e) Hazard analysis: This provides an identification and analysis of the hazards (radiological and non-radiological) associated with individual decommissioning activities, including waste handling and the identification of events that could activate these hazards. The hazard analysis addresses both normal, planned decommissioning operations and abnormal situations and incidents. A schedule should be included of all the hazards and fault/accident conditions that are applicable to the decommissioning activities; these may be grouped appropriately to reduce the number of scenarios that require analysis. Separate schedules for radiological and non-radiological hazards may be created. The likelihood of events and the nature and magnitude of the consequences arising as a result of each event should be identified, together with the safety systems that either prevent or protect against the scenarios occurring or mitigate their consequences.
(f) Assessment of potential consequences: This contains an assessment of the potential consequences in the form of radiation doses, physical injuries, etc. to the workers, the public and the environment from normal

decommissioning activities, as well as from the scenarios selected for accident conditions.

(g) Evaluation of results and identification of controls: The results of the safety assessment are compared with the relevant safety criteria, and, where necessary, the limits, controls and conditions needed to secure the safe conduct of decommissioning are identified. In establishing the limits, controls and conditions, it should also be demonstrated that the associated risks are ALARA.

(h) Preventive and mitigating measures: These specify the administrative measures and safety management programme needed to ensure safety. They include both passive and active SSCs and those that may require operator action to achieve their function. The impact of the preventive and mitigating measures on the likelihood or consequences of events needs should be described. These measures should be included in project documentation as the key safety control measures necessary for safe operations.

(i) Conclusion: This consists of a summary of the results of the safety assessment, including a statement on the acceptability of the decommissioning plan from a safety viewpoint.

2.8. SAFETY REVIEW

It is good practice for the safety assessment to be reviewed by experts other than those who contributed to its development. This independent review is normally carried out by, or on behalf of, the operator. There may also be a review carried out by, or on behalf of, the regulatory body. This is referred to in this report as a regulatory review to distinguish it from the operator's independent review. Annex III contains a detailed description of the regulatory review process; it includes a systematic procedure for review and examples of good international practice in this regard. On every occasion that there is a significant change to the safety assessment, an independent review should be carried out to confirm the appropriateness of the modified safety assessment.

An active decommissioning project is normally subject to an ongoing internal audit and reviews of various aspects of its safety, quality and environmental management. It will often be appropriate to perform the safety reviews at the conclusion of each phase of decommissioning work, to ensure that lessons learned at each phase are carried forward as the project evolves. However, if a phase is of long duration, intermediate reviews may also be appropriate. This approach may require the agreement of the national regulatory body.

2.9. CONTROL OF CHANGES TO SAFETY ASSESSMENTS

A decommissioning activity or operation may be changed or modified as compared with that planned in the original strategy and scope of work set out in the decommissioning plan. If such changes are safety related and affect the validity of the safety arguments, it is important that the original safety assessment is reviewed and, if necessary, modified to properly reflect and justify the changes to the plan.

A formal control process within the organization of the safety management programme is needed to ensure that changes are documented and controlled. This can be the same procedure used to document and approve safety related modifications to the facility during operation. Any proposed modification to the facility or to the procedures should be categorized in terms of safety significance, possibly using the same or similar criteria used for categorizing facilities and operations, and be subject to a similar independent assessment and approval process.

Once approved and implemented, any modifications should be added to the facility documentation. It is important that the limits, controls and conditions for safe decommissioning are updated to reflect the modifications. Similarly, it is important to bring the relevant operating instructions and the surveillance programme for decommissioning into line with the approved modified safety assessment.

2.10. STAKEHOLDER INVOLVEMENT

At many facilities, there is a requirement for independent assessment by specialists who are independent of the project or by a body (e.g. a standing committee) set up for this purpose. The regulatory body may also review, assess or approve the safety assessment. Other regulatory authorities, such as those responsible for regulating environmental discharges and for regulating industrial safety, may take an interest. Other stakeholders, such as the public living around the facility site, may have an interest in the results of the safety assessment. In some countries, there is a legal requirement that members of the public who may be affected by the project be consulted or informed by the operator before a licence for decommissioning is granted. This list of potential stakeholders is not exhaustive and may vary from country to country. However, it is prudent to identify and involve all significant stakeholders, both as an aid to planning and to help avoid project delays that might result from omissions in this context.

3. STEPS IN SAFETY ASSESSMENT

It is important to carry out the assessment of safety during decommissioning in a logical and transparent way in order to gain the confidence of the various stakeholders. A systematic approach for identifying potential hazards and for evaluating their consequences was shown in Fig. 1, and the main steps are described in more detail in the following sections. The steps are interdependent within an overall iterative process. Information from later steps in the process may result in modifications to the information used or developed in earlier steps, and the affected steps are then repeated in order to refine the assessment.

3.1. SAFETY ASSESSMENT FRAMEWORK

Before undertaking the safety assessment, it is important to specify the framework for the assessment. This includes a specification of the assessment context, the scope of the assessment, the objectives of the assessment, the time frames, the end states of the decommissioning phases, relevant requirements and criteria, the assessment outputs, the safety assessment approach, the safety management measures and the use of existing safety assessments. Guidance on the development of safety assessments is often published by national site owners, operators or regulators [19].

3.1.1. Context of safety assessment

The safety assessment forms part of a decommissioning plan, as described in Section 2.2. The safety assessment is carried out in the context of that plan, and, therefore, the scope of the safety assessment needs to be linked and to be consistent with the scope of the project decommissioning plan as a whole.

In some situations, the starting point for the safety assessment may be well defined, for example, at the end of operation of a facility for which comprehensive records are still available. In other situations, the condition of the facility may be unclear, and it may be necessary, as part of the overall decommissioning plan, to include an initial information/documentation gathering phase prior to performing the decommissioning of the facility.

3.1.2. Objectives of assessment

The objectives of the safety assessment for decommissioning may include the demonstration of safety to the operator, the regulatory body and the stakeholders, and serve as a basis for formal approvals, both from the regulatory body and from other regulatory agencies.

3.1.3. Time frames

Since decommissioning is often carried out in a phased manner, separate safety assessments may be required for different phases of a decommissioning project. For example, separate safety assessments might be performed for the initial cleanup phase, for dismantling, and for any subsequent institutional control and monitoring period. Safety assessments for succeeding stages of decommissioning may differ as hazards and mitigating systems are removed. The time frames for the phases over which the safety assessments are intended to be applied can vary significantly in duration. The effects of these different time frames must be taken into consideration in the safety assessment.

Consideration must also be given to the time expected for planning and achieving regulatory approval. Examples of expected time frames for planning and execution of decommissioning activities in various nuclear facilities are:

- Reactors: 2–12 a for planning and 1.5–5 a for executing the work.
- Hot cells: 2–3 a for planning and 5 a for executing the work.
- Fuel fabrication plants: 3–5 a for planning and 2 a for executing the work.
- Radioactive waste storage facilities: 3–5 a for planning and 2 a for executing the work.
- Radioactive waste management plants: 3–5 a for planning and 2 a for executing the work.

It is important to take the effect of possible time delays into consideration when the end points of the decommissioning are defined.

A key part of the planning stage is determining the work methods that will be used for decommissioning and for waste processing, handling and storage. A number of options may require evaluation. In such circumstances, a preliminary safety assessment of the options should be carried out to determine whether safety is a significant factor in the choice of work methods. In this report, it is assumed that the decommissioning work methods have been established, and that the final safety assessment is based on these already established work methods.

3.1.4. End points of decommissioning phases

The intended final end state of a decommissioning project and the end points of individual phases are important elements in planning the safety assessments that will be required over a complete decommissioning project. For a decommissioning project, the defined end point of one phase will be the starting point for the following phase. In such cases, the objectives and logic for each end point should be described.

Detailed information about the physical, chemical and radiological end state objectives is needed, irrespective of whether the safety assessment relates to the entire project or to an individual phase.

As an example, in the case of the multipurpose research reactor MZFR in Germany, the end state of the decommissioning was defined as a greenfield site. Decommissioning was to be performed in eight different phases. A safety assessment was required for each phase (see Appendix VII).

The end points for decommissioning phases depend on the choice of the final decommissioning or site end state, for example, the release for restricted or unrestricted use of the site. Where the end state is restricted use, a clear definition of the planned restrictions is important.

Guidance on appropriate radiological criteria for establishing end states is contained in Refs [16, 18, 20, 21]. Guidance on the acceptability of risk in this context (frequency and consequence) is contained in Refs [22, 23].

Decommissioning activities involving highly hazardous chemicals should also be subject to controls and, where appropriate, criteria for establishing end states should be specified [24–27].

International guidance can be found in a number of publications on: the regulation of decommissioning [3, 5–8], the regulation of radioactive waste management [2, 28–32], radiation protection [16, 20, 21], the application of the concept of clearance [17, 18], release of sites and buildings from regulatory control [18], and the legal and governmental infrastructure necessary for decommissioning of facilities [29].

3.1.5. Assessment outputs

The outputs of a safety assessment must correspond to its purpose. It is important to ensure that the chosen outputs, such as dose and risk estimates, safety control measures, etc., are adequately defined, since they represent an important link between the safety assessment and the decommissioning plan.

The safety control measures to be applied during the decommissioning should also be specified. In some cases, these will include some of those used during the operational phase, but in many cases, the operational control measures will no longer be relevant. In addition to the operational control measures, engineered systems and barriers sometimes have to be changed as a result of the safety assessment. Safety control measures include engineered control measures, and these will also change as decommissioning proceeds and physical barriers and plant SSCs are removed.

3.1.6. Safety assessment approach

The nature of the output measure should be clearly defined, but, in addition, the nature of the approach used to determine the output measure should be clear. In particular, it is necessary to specify the nature of the overall approach that is used for the safety assessment. Different approaches can be applied in safety assessment to estimate the potential radiological and non-radiological impacts of decommissioning activities on workers, the public and the environment:

— A deterministic approach, in which the lines of defence against accidental activity release or exposure are identified, is the approach that has been most commonly applied in the safety assessment of facility decommissioning [22]. This approach focuses attention on the integrity and robustness of the claimed lines of defence, and provides a clear demonstration of the failure tolerance of the safety assessment.
— A probabilistic approach can be used to complement the deterministic assessment, but should not replace it, other than for application to accident sequences within a defined low consequence/occurrence frequency where risk criteria are met without additional control measures being required. A probabilistic approach can be used as a tool to screen or eliminate accident scenarios for which the overall risk is shown to be acceptably low, so that no further safety assessment is required. The unmitigated consequences (without control measures in place), together with an estimated frequency of occurrence, are compared to accident risk criteria to determine whether further analysis is required or not.

3.1.7. Existing safety assessments

For facilities that already have a safety assessment for the operational phase, parts of that safety assessment may be relevant to aspects of the decommissioning safety assessment. However, it is important to recognize that the activity of decommissioning is fundamentally different from that of operating the facility. Engineered barriers, which are credited in the safety assessment for the operational phase of the facility, can become ineffective, particularly once invasive work commences. Depending on the decommissioning technology used, there may be new hazardous materials (e.g. solvents and combustibles) brought into the facility. Radioactive contaminants or other hazardous materials, which were not mobile during operations, can be converted to more dispersible forms during the decommissioning process. It is important to recognize and account for these hazards during the preparation of the safety assessment. It must also be borne in mind that new supporting facilities and equipment, not covered by the operational phase, may be required for decommissioning and may have to be developed for the decommissioning phase.

Safety assessments may also have been performed previously for the decommissioning project, for example, as part of an earlier conceptual or preliminary decommissioning plan. Such earlier safety assessments can be very valuable as starting points for the planning of new safety assessments. Therefore, it is important to keep these up to date during the operational phase, especially as far as modifications and utilities are concerned.

3.1.8. Safety management measures

The site operator's safety management system is used to ensure that work on the site is carried out in a safe manner and in compliance with legal requirements. It includes such components as task level procedures, change control procedures, work control procedures, PPE, training and testing programmes, radiation protection programmes, occupational safety programmes, criticality control programmes and emergency preparedness programmes. The safety assessment is performed assuming that the site's safety management programme will be complied with for all of the decommissioning work. The safety management system represents an important link from the safety assessment back to the project decommissioning plan. For example, the results of the safety assessment could be used to modify and improve the management of procedures and processes.

3.2. DESCRIPTION OF FACILITY AND DECOMMISSIONING ACTIVITIES

A description of the facility and its associated land, structures, buildings and safety related equipment to be decommissioned is essential in providing a good understanding of the facility covered in the safety assessment. The first detailed post-operational facility description is usually contained in the facility decommissioning plan. Detailed analysis may be required of the source term geometry, radioactivity concentrations and estimated timescales per decommissioning task or group of tasks in order to be able to calculate exposures to sources of internal and external exposures to workers and the public. The facility description should also address the physical, chemical and social environment in which the facility is situated. A good quality description of the facility and the decommissioning activities to be carried out is also needed for defining the potential hazards and establishing parameters and features for the modelling used in the safety assessment. The level of detail for the facility description should be commensurate with the level of hazard presented and the complexity of the facility, but should be sufficient to permit a representative safety assessment to be performed. It is also important to include information on all parts of the facility that are to be decommissioned, since the description may be used to define the scope of the work and also to identify any facility or building(s) to be excluded from decommissioning.

Typically, information about the facility is derived from the operational safety assessment, from operational records and from detailed post-operational surveys and ongoing decommissioning activities. In some cases, such as legacy facilities where the information available is inadequate or insufficient to serve as the basis for an assessment (such as lack of design drawings), reliance has to be placed on assumed or generic values of certain parameters. In such cases, analysis of the uncertainty introduced by such assumptions is very important.

3.2.1. Site description and local infrastructure

The precise location of the facility and its relationship to other facilities at the same site should be described. This includes descriptions of nearby facilities, structures (above and below ground) and buildings in which there can be persons or equipment that could be affected by events occurring during the decommissioning activities. Detailed surveys of the radiological and engineering status of the facility may be necessary depending on the transition phase between the shutdown of the facility and the planned decommissioning activities and the nature of the planned decommissioning activities.

The locations of potentially affected members of the public near the site should also be defined. This includes information relevant to the atmospheric dispersion of airborne releases, such as meteorological information, and information on distances and directions to potential exposed population groups. Transport routes for equipment and radioactive materials, both off-site and on-site should also be described. If the decommissioning activities could result in radioactive or hazardous materials being released to surface water or groundwater pathways, the geological, hydrological and hydrogeological state of the site should be characterized.

Relevant information for the safety assessment of external hazards such as natural hazards (extreme cold, earthquakes, flooding, fires, etc.), transport routes (aircraft crashes, etc.) and industrial activities should be updated and compiled.

The information should also include:

— Assessment of existing facility conditions and inherent hazards by performing a detailed facility walkthrough, including radiological and toxicological surveys, by a multidisciplined team that includes the project manager, engineering representatives, health and safety personnel, and workers;

— Documentation of the hazards associated with planned decommissioning activities.

3.2.2. Safety related structures, systems and components

A description of the safety related SSCs that are to be decommissioned, including a description of any buried structures at the facility site, should be prepared. This includes the existing configuration of SSCs in sufficient detail to support the safety assessment. Any degradation or other changes, and plant modifications relative to the original design should be identified.

A description of existing and new SSCs that will be needed to prevent or contain the spread of radioactive or hazardous materials during decommissioning is also required, including descriptions of interdependencies among SSCs. The key safety control measures will be an output of the decommissioning safety assessment.

Common equipment being dismantled, which is structurally linked to other equipment that will be left until a later phase(s) of decommissioning, should be described, together with the means by which the integrity of the remaining structures will be ensured.

3.2.3. Radioactive inventory

A detailed description of the locations, amounts and characteristics of existing and expected radioactive and other hazardous materials at the facility should be provided. This includes the distribution of this material within the facility and within individual structures and equipment. This information should be based on both operational records and the results of field surveys. It is also important to include previous process modifications and incidents that led to the contamination of areas that had been previously decontaminated, but which may not comply with the requirements for the desired end state of the facility.

The description should also include any characteristics of surface and subsurface contamination of soil and groundwater, and of any radioactive or hazardous materials that were buried on the site. If any radioactive waste or spent fuel has not been removed from the site prior to decommissioning, it should be clearly specified whether these materials are within the scope of the assessment. This inventory facilitates the design of suitable radiological protection measures for later activities.

It is not always possible to detail the radioactive inventories at the outset of decommissioning for various reasons, for example, contamination in pipes previously used in fuel cycle facilities. If only estimates are available, allowances should be made for the associated uncertainties in the models and calculations used in safety assessments. The safety assessment should include information on the estimated size and nature of the uncertainties and indicate how they will be managed, in terms of both procedural controls and subsequent revisions, to the safety assessment.

Periodic updating of the radioactive inventory is generally performed when new data can be collected during the performance of the decommissioning activities. The methodology proposed for the various measurements to be made (of alpha, gamma and beta emitting radioactive material), and the instrumentation and sampling techniques to be used, should be described. If the new inventory estimated during the decommissioning activities is significantly different from the preliminary estimates, a revision of the safety assessment, especially when several phases are planned, should be performed.

3.2.4. Operational history

Relevant information from the operational history of the facility should be compiled relating to the state of structures, systems and equipment, and information on modifications to the design and records of accidents or incidents that have a potential impact on the safety of decommissioning. This information should include:

- An assessment of the existing facility status by collecting and reviewing available facility operating records and other relevant documentation;
- Records of modifications to the facility carried out during the operating period and identification of any modified equipment important for the safety of the decommissioning activities;
- Assessment of records of incidents or accidents and associated corrective actions;
- Post-operational radiological survey data;
- Assessment of existing facility conditions and inherent hazards by performing a detailed facility walkthrough, including radiological and toxicological surveys, using a multidisciplined team that includes a project manager, engineering representatives, health and safety personnel, and workers;
- Operational documentation of the hazards within the facility relevant to planned decommissioning activities;
- Review and consideration of applicable lessons learned from reports of events during facility operation, as well as for similar facilities;
- Interviews of past and present employees, as necessary, to supplement information on past facility operations, including mishaps and incidents.

It is important to obtain information about the location of radioactive contamination at the facility, both as a result of normal operations and from incidents or accidents. Gaps or uncertainties in the available information should be clearly identified.

3.2.5. Decommissioning activities and techniques

Since decommissioning activities could be a potential source of exposure, it is important that these activities be sufficiently well described in advance, so that all significant hazards can be identified and addressed in the safety assessment. The description of decommissioning activities should be sufficiently detailed to ensure that safety assessments are soundly based.

The description should include the major phases of decommissioning, such as the removal of major hazards (e.g. spent fuel, if this has not already been done during the operational phase); decontamination, including the removal of fixed contamination from surfaces and equipment; dismantling of systems and equipment; demolition of structures; and remediation of residual contamination on the site (see Appendix III — a Canadian example).

At a more detailed level, the description of the decommissioning techniques should also include items such as:

- Decontamination and cleanup techniques to be used;
- Dismantling techniques to be used, such as cutting methods;
- Materials processing, packaging, storage and on-site handling activities;
- Maintenance of supporting systems;
- Modifications to structures and systems to accommodate changes in the facility configuration.

Any need for power, cooling water and other external supplies for the equipment used in decommissioning should be documented.

3.2.6. Supporting facilities

New supporting facilities that are required for the purpose of safe decommissioning should be included in the safety assessment, for example, radioactive waste storage facilities, laboratories, size reduction facilities, etc. These facilities and any hazards related to their construction and operation will require their own safety assessment. Likewise, if existing SSCs are to be used in decommissioning, they should be included in the facility description. If existing structures or systems need to be modified for decommissioning purposes, the modified plant should also be included within the safety assessment.

3.2.7. End state

The end state of a facility/site following completion of decommissioning should be described within the framework of the safety assessment and the decommissioning plan. In some cases, the end state is unrestricted use of the site and its release from regulatory control. In other cases, the intended end state may be restricted release, and some form of institutional control will remain. For example, the end state could be restricted use because the site has a temporary waste storage facility left on it.

When the tasks and activities set out in the decommissioning plan have been completed, appropriate measurements will be required to demonstrate that the residual radionuclides at the facility or site have been removed and that the end state conditions specified in the decommissioning plan have been met.

When significant amounts of radioactive material are to remain on the site, a safety assessment for the post-decommissioning state will be required.

3.3. HAZARD ANALYSIS: IDENTIFICATION AND SCREENING

3.3.1. Hazard identification

One of the first steps in developing a safety assessment for decommissioning activities is the identification of existing and future hazards[7] (both radiological and non-radiological) that can affect workers, members of the public and the environment during decommissioning activities under normal and accident conditions. It is critical to the safety assessment that all reasonably foreseeable initiating events and accident scenarios are identified. The main groups of radiological and non-radiological hazards to workers, the public and the environment are mentioned below. The following hazards are a subset of the more complete list of hazards and initiating events given in Appendices VIII and IX:

(a) Radiological hazards:
   (i) Criticality: The occurrence of accidental criticality is not envisaged in shutdown nuclear reactors from which the fuel elements have been completely removed, including their removal from associated stores.

[7] The term ‘hazard’ used in this report means an intrinsic property of a facility, activity or process, with a potential for creating damage to human health and/or the environment.

The possibility of accidental criticality can exist, however, in the process equipment or waste storage tanks of facilities where fissile materials have been processed, such as fuel manufacturing plants, spent fuel reprocessing plants or fuel enrichment plants.

(ii) Direct exposure: The presence of source materials, activation products and contaminants can pose direct radiation hazards during decommissioning activities, as well as in abnormal and accidental conditions. For example, irradiated stainless steel components of a reactor can cause direct radiation exposure of workers.

(iii) Internal exposure: If radionuclides are present in the work area in the form of removable surface contamination, workers and the public can be subjected to internal radiation exposure by ingestion or inhalation. The hazard from inhalation is of particular concern in the case of activities carried out in areas or premises contaminated with alpha emitting radionuclides.

(iv) Liquid and gaseous radioactive effluents: Some of the waste generated during the decommissioning of a facility can have different forms and characteristics to those generated during operations. This is because the materials involved in decommissioning and some associated activities (e.g. cutting and decontamination) can be different from those employed during the operating stage. In addition, the amounts of liquid effluents generated from decontamination operations can be larger during decommissioning than in the operational phase, while the amount of gaseous effluent generated from ventilation of work areas is usually smaller than during the operational phase.

(v) Erroneous free release of materials: Some materials, such as concrete and metals, can be freely released, i.e. removed from regulatory control, if their activity content is below clearance levels [16]. The potential for erroneously releasing material with activity content in excess of these clearance levels has to be identified in the safety assessment.

(b) Non-radiological hazards:

(i) Combustible and flammable materials: Fire is the conventional hazard that is of most common concern in facility decommissioning projects. The methods used for certain equipment dismantling operations (e.g. thermal cutting techniques) or for decontamination of surfaces (e.g. use of aggressive decontaminating solutions) are often the cause of local fires. Moreover, while dismantling activities are in progress, the temporary accumulation of combustible materials and waste (e.g. plastic and cotton) is common, thus increasing the potential for fires in the area. In addition, explosions can occur during decontamination and dismantling as a result of the chemical reagents and equipment used. Some materials generated in the process of dismantling a facility, such as inflammable dusts, can, in certain circumstances, acquire explosive characteristics.

(ii) Toxic and otherwise hazardous materials: The dismantling of facilities sometimes reveals that they were built using materials that are now forbidden and the removal of which requires special measures because of their toxic or otherwise hazardous properties. It is common, for example, to find asbestos in thermal insulation or in fire barriers, lead in paint, counterweights and shielding, and polychlorinated biphenyls in oils and electrical insulation. Furthermore, some of the materials used in the decommissioning process, such as decontamination chemicals, may be toxic and hazardous.

(iii) Electrical hazards: The use of power sources and electrical equipment during decommissioning can pose a general hazard to workers, which must be recognized and addressed effectively. Temporary electrical equipment used during decommissioning activities can increase this potential hazard.

(iv) Physical hazards: During decommissioning work, physical hazards exist that are typically associated with demolition activities or with the construction and use of temporary facilities, for example, collapse of structures, falling of heavy objects, injury from sharp objects, occurrence of abnormal events during the use of material handling equipment and hazards due to falling from heights.

(v) Natural hazards: The natural hazards that were considered for the operational phase of the facility may still be relevant, and some, for example, flooding, may, at some phases of decommissioning, present a higher risk than they did during operation.

Depending on the initiating events and specifics of the accident conditions, these non-radiological hazards may cause or exacerbate the release of radioactive materials. For example, fires involving combustible materials can cause a failure of containment equipment or systems.

The various hazards mentioned above, as well as other relevant ones, should be evaluated by considering potential initiating events such as equipment and system failure, utility failure, integrity failure, operator errors and external factors.

3.3.2. Approaches to hazard identification

Hazards associated with individual decommissioning activities can be identified by using appropriate approaches, and methods include the following:

(a) Evaluation based on the existing safety assessment for the facility: If a safety assessment for the operation of the facility exists, this assessment can be used as a starting point. Many of the hazards relevant in the operational phase may no longer be relevant, but some potential new hazards will have to be added.
(b) Evaluation based on past operational experience: Knowledge about incidents or accidents that occurred during the operation of the facility are useful in identifying certain hazards, such as radiation sources, that will be met during decommissioning work.
(c) Use of checklists: The use of checklists can be a useful approach for identifying hazards and initiating events for both experienced and less experienced individuals. For small facilities with few radioactive sources, a checklist can be a sufficient means for hazard identification. When assessing individual decommissioning activities in a larger facility, checklists can also be useful. Appendix VIII presents a generic checklist of hazards that may be relevant for decommissioning operations. This list can be used as a starting point for hazard identification at a given facility, but care needs to be taken to add hazards that may be relevant for the particular facility. Since hazards may vary during decommissioning, the checklists have to be reviewed for each phase/stage of decommissioning.
(d) Hazard and operability study (HAZOP): This type of study is mainly used for an operating plant as a tool for hazard identification [26, 27]. It is usually carried out by a team of 4–6 people, including a trained leader (with safety and reliability experience) and individuals involved in the design and the operation of the process to be studied. For a decommissioning process, the operations would include cutting, lifting, cleaning and transport.
(e) The ‘brainstorming’ approach: This technique is often termed the ‘what if?’ approach, and is best performed by a group of experts familiar with the equipment and the facility to be decommissioned. The technique can be combined with a checklist analysis to increase the efficiency of hazard identification. This combination is referred to as the ‘structured what if?’ technique. ‘What if...?’ questions may be asked within categories, although there is no need to stick to this rigorously; possible categories are:
    (i) External factor influences;
    (ii) Operator error and other human factors;
    (iii) Equipment/instrumentation failure;

(iv) Utility failures;
(v) Integrity failure.

An example of a hazard identification approach is presented in Fig. 4, including the steps of hazard evaluation that follow the hazard identification.

It is important to place particular emphasis on identifying hazards that could be created or exacerbated by the:

— Decommissioning activities undertaken, such as during the transition from one decommissioning phase to another, use of common systems between facilities, loss of barriers, potential for interaction between many works taking place simultaneously, etc.;
— Deterioration of SSCs, or chemicals left in process lines or storage tanks causing corrosion of equipment or changes in form;
— Premature removal of safety features such as engineered systems (e.g. firewalls or containment barriers);
— External events (e.g. floods, storms).

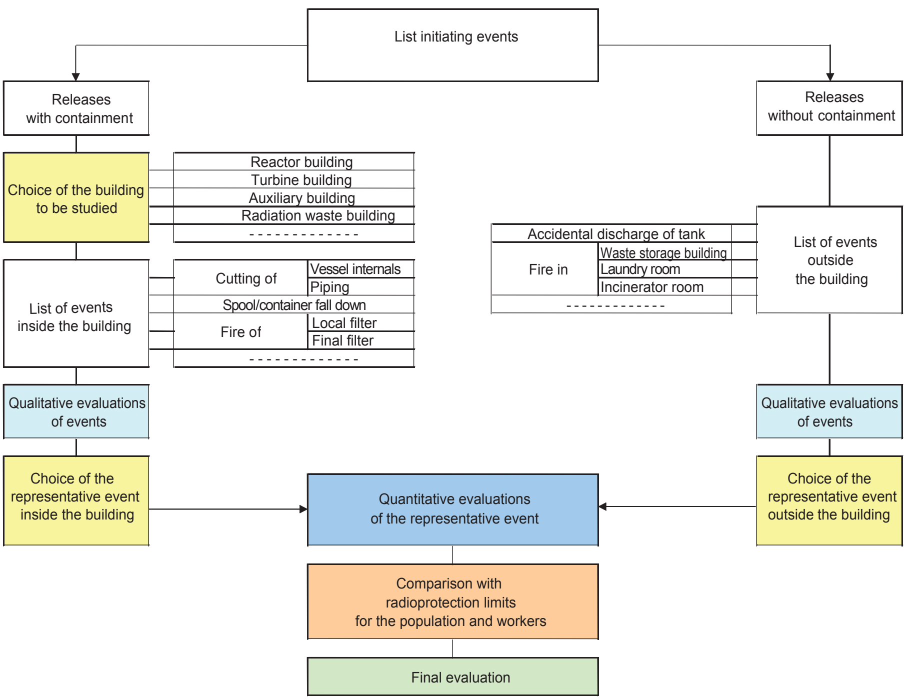


FIG. 4. Example of a hazard identification approach (adapted from Ref. [33]).

During the transition phase from operation to decommissioning, hazardous materials (e.g. asbestos, polychlorinated biphenyl, oil, etc.) can be removed, which will reduce the hazards and simplify the safety assessment for decommissioning [34].

In some cases, additional characterization activities will be necessary to properly identify potential hazards where there is inadequate knowledge about hazardous materials at the site, e.g. radioactive material, hazardous chemicals or asbestos. Making conservative assumptions about the material amount or form, or assuming a piece of safety equipment will not function can sometimes be an effective strategy to allow the safety assessment to proceed without further characterization, but it may be necessary to introduce investigations as work progresses to ensure that any such assumptions remain valid.

In addition to the hazards related to the systems or physical phenomena, a number of less direct issues can affect the safety of a decommissioning project. Human errors can occur due to misunderstandings or due to a lack of concentration. The safety culture in the organization, including attitudes of staff and management to safety, can influence the risk of accidents occurring as a result of human failure. In addition, the economic situation may have an influence, for example, if funding is not sufficient.

All identified hazards should be recorded in a systematic manner, such as in the example provided in Appendix X, which also identifies the control measures used to prevent or mitigate the effect of hazards.

3.3.3. Preliminary hazard assessment and screening

A preliminary safety assessment of hazards is useful to predict the bounds of potential consequences and to identify whether detailed analysis is required. Appendix IX shows examples of hazards and risks associated with typical decommissioning activities. Having identified the relevant hazards, a system such as the one shown in Appendix X can be used for detailed evaluation of the hazards. Table 12 in Appendix X can be finalized once the safety assessment has developed to the stage where safety control measures have been demonstrated to be robust and sufficient.

Low risk accident scenarios do not usually require further safety assessment, as at low risk levels, the safety control measures introduced as part of the operator's safety management programme are generally sufficient to minimize risk.

A risk classification system, such as that in Appendix XI, can be used to determine requirements for when further safety assessment is needed, circumstances where no further assessment is required, the level of control measures required and the level of regulatory approval of the safety assessment.

For example, facilities with the potential for a significant off-site risk require the highest level of scrutiny, and may ultimately require the agreement of the national regulatory body.

In more complex facilities, the number of potential accident scenarios can be large, although it is not always necessary to assess them all. They can often be grouped so that representative bounding accident scenarios can be identified for analysis, so that the amount of assessment and analysis effort is optimized. Similarly, accident scenarios can be screened out (i.e. not selected for analysis) on the basis of low potential consequence and/or a very low frequency of occurrence.

If fissile materials remain at the facility, criticality hazards have to be considered if the minimum theoretical mass values necessary for nuclear criticality to occur could be exceeded. Reference [13] suggests minimum values below which a safety assessment is not needed.

Situations can occur where chemicals are used in large amounts or have a high hazard potential, such that the associated initiators and accident sequences require detailed assessment. An example is the treatment of liquid metals used as the coolant in fast breeder reactors.

When working with chemicals and other hazardous substances, safety controls are normally addressed in the legislative requirements applying to the usage and storage of such substances [15]. The operator's safety management programme should contain procedures to ensure compliance with the legal requirements on chemical and hazardous substance use.

3.4. HAZARD ANALYSIS: EVALUATION

At this point of the safety assessment, the potential hazards and initiating events have been identified, and a bounding preliminary assessment of consequences and frequency of occurrence has been carried out. The accident scenarios that are shown to present a low risk require no further assessment, but those in the higher risk categories need to be evaluated. Accident scenarios have to be developed for all initiators, but it is desirable to group them as far as is sensible to minimize the number of separate scenarios that require analysis. The radiological exposure of workers and of the highest exposed group in the local population, using the 'critical group' concept [16], should be evaluated. For planned activities, the exposure of workers should be calculated on the basis of agreed and documented work tasks. Examples of typical ways in which occupational exposures can arise are shown in Appendix XII.

3.4.1. Analysis of normal activities

Normal activities within the context of decommissioning can be defined as ‘any activities that are planned and scheduled through the work control process’ (i.e. not as a result of emergency action or in response to accident conditions). Assurance of safety in normal planned decommissioning activities and tasks is largely achieved through compliance with the established safety criteria and the site safety management programme (e.g. radiation protection, conduct of operations, training and qualifications, and quality assurance). The radiological protection of workers during normal operations is achieved by implementing occupational radiation protection procedures [16]. The work control process ensures that each task is conducted in a safe manner in accordance with all pertinent requirements and control, so that doses are kept below regulatory limits.

Any planned discharges of radioactive or hazardous materials to the environment are subject to regulatory control procedures aimed at ensuring that radiation doses to members of the public are below dose limits and follow the ALARA principle [16]. The evaluation of the radiation dose to the most exposed group in the local population (the critical group) is carried out using computer codes or other methods, i.e. the same methods as used for the operational phase of the facility.

3.4.2. Analysis of accident scenarios

Following the analysis of normal scenarios, as described in the previous section, the next step is to develop and analyse a set of accident scenarios that encompass all reasonably foreseeable unplanned events and accidents that could result in exposure.

Similar accident types should be grouped to limit the number of accident scenarios to be analysed. As a first step, accident initiators are sorted into several categories, such as:

(a) Operational accidents (e.g. initiated by plant failure, fire, operational error) within the facility;
(b) Human-made external events (initiated by activities outside the facility that may or may not be related to facility operations);
(c) Events initiated by natural phenomena.

These categories of events could be further subdivided, for example, operational accidents could be further divided into fires, spills and explosions, and possibly subdivided into accidents inside containment and accidents in facilities without containment. Within each of these categories, accident scenarios are further grouped in such a way that each group can be represented by a single accident scenario (‘worst case scenario’) whose consequences will represent (or exceed) those of other scenarios in the group.

Once an accident scenario is selected for accident analysis, it is characterized and analysed to evaluate the consequences. This characterization covers the amount of material, the physical form and composition of the material, the physical surroundings that affect the material behaviour and release characteristics, and the initial set of assumptions used to perform the modelling. The description of the accident scenario should include the following information (an example is given in Appendix X):

— Accident type;
— Accident duration;
— Causes and activities;
— Preventive control measures;
— Termination of accident;
— Mitigating control measures;
— Frequency;
— Consequences;
— Assumptions necessary to support the calculation of consequences.

The accident analysis should be as broad and as bounding as necessary to capture the applicable features and hazards of similar accidents. It is important to present the accident analysis in a realistic and plausible fashion. The selection and description of the accident scenarios should be documented; the description should include the scope or range of initiators to be covered. This serves as a basis for the subsequent evaluation of proposed changes and for any changes following the discovery of omissions and unexpected conditions during decommissioning.

3.4.3. Modelling and calculation of consequences

Modelling in hazard analysis establishes a link between activities or activity concentrations in materials and radiation doses to people. The doses can then be compared with dose limits/dose constraints. Alternatively, the authorities may prescribe activity concentrations in environmental media with which the results of the models have to be compared. The level of complexity of these models varies according to the type of decommissioning project, requirements of the authorities and other issues.

It is worth distinguishing between two assessment objectives of modelling and calculation:

(a) The hazards resulting from decommissioning activities;
(b) The hazards associated with the end state, i.e. the assessment is directed to evaluating the potential impact of the radioactive material that remains in the buildings and soil after decommissioning has been completed.

The latter objective becomes relevant only if such calculations are required in order to justify the release of the facility or site from regulatory control. This is the case in some Member States, while other countries rely on established clearance levels [17] that have been derived on the basis of calculations for generic scenarios. For end state calculations, long term transfer mechanisms have to be evaluated, and assumptions have to be made concerning the future behaviour of people living near or at the site.

To evaluate radiation exposures due to planned activities and potential accidents, calculation models may need to be developed that describe the following main components:

— The radioactive inventory of the facility (i.e. location, dimensions, spatial distribution, constituents, amounts);
— Activities of the representative person (e.g. habits);
— Radionuclide transport processes in the atmosphere, hydrosphere and soil;
— Exposure pathways (i.e. external exposure, inhalation of the plume, external exposure to deposits from the plume, ingestion of contaminated food and water).

In many situations, however, simple bounding calculations may suffice, thus avoiding the need to use complex computer codes.

For evaluating radiation doses from releases to the environment, models have to take into account the source term, the distribution of the radionuclides in the environment, the transfer to humans and finally the evaluation of radiation dose. A number of computer codes and prescriptions for calculations are available. The complexity of these calculation procedures and computer codes is usually adjusted to the complexity of the type of facility to be assessed.

In order to perform in depth analysis of exposures to radiation from external sources to workers, it may be necessary to specify the time spent per work task in a specific area. For internal exposures of workers, it is necessary to estimate the time spent by persons in a specific area and to calculate the airborne concentration and the mixture of isotopes present. The information must be derivable from the facility information provided (Appendix XIII).

Many models exist for assessing the impact of discharges of radionuclides to the environment through air, water, and terrestrial and aquatic foods, including the IAEA's generic modelling guidance [35].

The techniques and computer tools used for evaluating the safety of a specific facility should be commensurate with the associated hazards and complexity of the facility, as well as with the availability of data. For instance, a fire in a room or compartment can be modelled using a computer code (e.g. Ref. [36]) to obtain the spatial distribution of a temperature profile simulating the growth of fire. Such information is useful for evaluating the thermal integrity of the internal systems within the room where the fire is postulated to occur. Alternatively, simple bounding assumptions on release fractions can be used if acceptable results from the assessment are achieved. Another example is the calculation of particle transport phenomena to yield realistic leakage estimates through confinement or filtration media (e.g. Ref. [37]).

For very complex projects, computerized mathematical models can be used to quantify the consequences of the release of radioactive material as a result of decommissioning activities (see Fig. 5). The mathematical model should be chosen to adequately represent the conceptual model and the exposure scenario. The parameter values used should be justified based on the available knowledge of the facility and the site, as well as any assumptions and simplifications that are used in the development of the mathematical models and their implementation in computer tools.

Uncertainties related to individual models, computer codes, representations of working conditions and values of facility and transfer data should be identified and treated as appropriate. Probabilistic models using simulations of parameter variability can be used when appropriate.

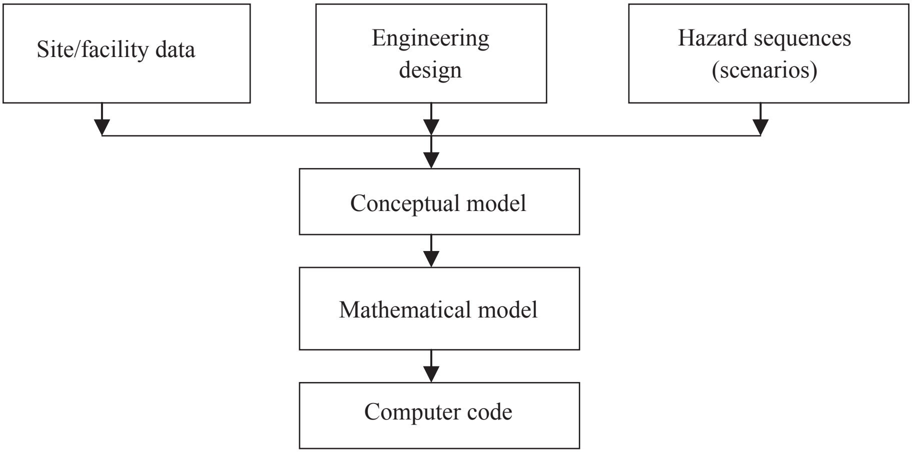


FIG. 5. Model development.

The degree of conservatism in mathematical models or computer based software is an issue that must be taken into account in the safety assessment, since the use of highly conservative approaches will result in approximations of real world conditions, which may lead to more costly precautions than necessary.

3.4.3.1. Computer codes

Computer codes also have to be distinguished according to their purpose:

— The facility inventory and its distribution (e.g. for a nuclear power plant) are evaluated by estimating the neutron induced activity in the reactor core, its components and its surrounding structures. There are various computer codes available for the estimation of the neutron activation. The resulting data should be rearranged into the structure of the decommissioning inventory database in order to be usable for calculation of the decommissioning parameters and evaluation of the safety of performing the decommissioning activities.
— For use in the planning phase, radiation doses to workers and to members of the public from the entire decommissioning project should be evaluated to demonstrate that the planned decommissioning activities are, in principle, safe. This requires a broader scope approach and a lower level of detail than subsequent analyses. It is suggested that the results of the evaluations are presented in a standardized format [38, 39].
— For detailed optimization of the work plans of decommissioning activities (within the various phases of the decommissioning project and of the entire decommissioning project), including detailed evaluations of radiation dose rates for dismantling activities.
— For environmental and radiological impact assessment.
— For the evaluation of specific issues, e.g. fire, explosive, chemical phenomena and collateral effects assessments covering both radiological and chemical aspects.

Environmental safety assessment can be performed at different levels depending on the phase of the decommissioning (planning, detailed works, etc.) and on the site specific data available. For example, the calculation method in the IAEA's Safety Reports Series No. 19 [35] does not require very detailed site specific data, and could be used for facilities with a small radioactive inventory (and lower associated hazard). More complex codes should be used for facilities with a higher hazard associated level in order to improve the accuracy of dose estimates. Examples of such codes are contained in Refs [36, 40–77].

3.4.3.2. Quality control of calculations

When computer software models are developed, independent specialists should review and verify the basic model and input data, as well as the assumptions made. The use of the model and any limitations should be documented. The safety assessor should justify the use of a model by reference to this formal verification documentation. If a computer code is not well known or published by credible organizations or institutes, its use should be avoided, if possible. If its use is required, then its verification and validation should be documented; this could be included as part of the operator's management programme (see Section 5). The intended application of the code should be compatible with the actual conditions for which the code is applied. Users should have proper training in the use of the codes to avoid serious effects on the quality of the results obtained.

3.4.3.3. Requirements for calculations by regulatory authorities

The level of detail at which national competent authorities prescribe the methods to calculate doses/risks and the use of computer codes for hazard analysis varies considerably. In some cases, the calculation procedure is defined in great detail, while in others, it is left to the discretion of the licensee. For example, in Germany a rather detailed prescriptive approach is used [78–81], while in the United Kingdom, the responsibility is mainly left to the licensee to devise his/her assessment approach.

3.5. ENGINEERING ASSESSMENT

The safety assessor should specify the necessary safety related functions, and any performance requirements, of each engineered safety control measure (SSCs). For a complex assessment, it is good practice to document these requirements in a single report that can act as a functional specification for the engineering specialists. Following on from this, an engineering evaluation should be performed to demonstrate that the safety and performance requirements specified by the safety assessor can be provided by each engineered safety control measure, as expected.

It is normal practice to categorize SSCs in accordance with the importance of the safety function that they will be required to provide. This allows a graded approach, so that engineering expertise and effort can be applied proportionately to the safety significance of the SSCs. The operators may devise their own engineering assessment processes, as there is no universal international standard in this area, but an example is given below for information and consideration.

Example:

(a) SSC category 1: Those SSCs that are the principal means for the prevention/mitigation of significant public exposure and major worker exposure; typically applied for risk class I accident scenarios (see Appendices XI and XIII for risk classification). Category 1 SSCs are not usually to be expected in a decommissioning safety assessment.

Requirement: Engineering assessment to be supported by detailed engineering investigations and calculations, assessment against national engineering codes and standards, review of operational experience, specification of surveillance programme requirements and a demonstration of fitness for purpose in meeting functional requirements under accident conditions.

(b) SSC category 2: Those SSCs that make a significant contribution to the prevention/mitigation of decommissioning worker exposure, other workers on the site but a lesser public risk, where the risk is commensurate with risk class II accident scenarios. Category 2 SSCs may be required in decommissioning safety assessments, but will not be commonly found in decommissioning applications.

Requirement: The requirement is similar to SSC category 1 items, but with an appropriately lesser level of detail in the engineering assessment.

(c) SSC category 3: Those SSCs that only have a minor contribution in the prevention/mitigation of worker exposure; typically applied to risk class III accident scenarios. This will be the category of SSCs often found in decommissioning safety assessments.

Requirement: The requirement will be to demonstrate adequate functionality and performance, only based on records and/or a structured facility walkdown to demonstrate that the facility is in good condition and in accordance with engineering drawings.

(d) SSC category 4: Those SSCs that make only slight contributions to the prevention/mitigation of worker exposure. Category 4 SSCs may be applied in risk class IV accident scenarios.

Requirement: The only requirement is to register the SSCs in the facility surveillance programme, and they may only be required to be considered for a response when they become non-functional.

If an SSC is provided by new facility engineering, assessment by the operator is not needed. However, the design documentation should be in accordance with the appropriate national engineering codes or standards, together with a demonstration that the safety and functional requirements of the SSC specified in the safety assessment are satisfied. The details in the engineering assessment demonstrating compliance with functional and performance requirements should be proportionate to the SSC category.

When the engineering assessment is complete, the basis upon which the SSCs have been shown to be capable of meeting their performance and functional requirements should be documented, and included in or referenced in the safety assessment. Any surveillance programme requirements, such as periodic inspection or testing of the plant and systems, should also be specified and included in the surveillance programme.

3.6. EVALUATION OF RESULTS AND IDENTIFICATION OF SAFETY CONTROL MEASURES

The results of the safety assessment serve to demonstrate compliance with regulatory requirements and to define those control measures necessary to demonstrate compliance and to show that risks have been reduced to ALARA. The results of the safety assessment will normally be adjusted by the application of control measures, until the analyst is satisfied that all criteria are shown to be met and that risks are according to the ALARA principle. The uncertainties and assumptions made should be identified and documented, and any required improvements implemented. Additional controls identified as being necessary to mitigate the consequences of accident sequences, abnormal events and incidents should be evaluated and shown to be fit for purpose.

3.6.1. Type and treatment of assumptions and uncertainties in safety assessment

A safety assessment will normally contain a significant number of assumptions on matters such as plant integrity, age and conditions, consequence of events and validity of data. Overall, the safety assessment should be conservative, though not normally unduly so, unless this allows the safety assessment to be simplified and gives overall benefit to the decommissioning project. In the decommissioning of facilities, the detail ideally required for safety assessment is not usually present, and this has to be compensated for by the use of bounding assumptions or a strategy in which intrusive work is carried out to establish aspects of plant condition and activity that are needed for the safety assessment. It is, however, possible to make a set of assumptions that can be shown to result in a sufficiently conservative safety assessment. Examples of where significant uncertainties exist are:

- — Condition and construction of building structures and systems — where it is important, some site operators have adopted ‘ageing management programmes’, so that the additional risk from the degraded plant and structures can be soundly managed;
- — Detailed facility knowledge due to inadequate design records;
- — Uncertainty in nuclear material inventory and location;
- — Volumes of different waste streams that will arise;
- — Activity levels and radionuclides in an inaccessible plant;
- — Uncertainties in analysis models and codes;
- — Sensitivity to human errors in planned work.

The assumptions made within the safety assessment have to be documented and justified. This ensures that reviewers can conduct a complete assessment and reach a sound conclusion on its acceptability. Where the outcome of the safety assessment could be significantly affected by assumptions and data used, it is appropriate to carry out additional ‘sensitivity analyses’ to ascertain the effect of varying such assumptions and data within their credible ranges. If compliance with safety criteria can still be demonstrated when these extreme assumptions are made, the safety assessment is sound. Otherwise, it will need to be reassessed, and other means determined for achieving compliance with criteria.

Uncertainties in nuclear material inventories or the presence of other hazardous materials are often encountered in decommissioning work, and their significance to the planned work and its supporting safety assessment has to be determined.

Where the range of uncertainty in an important aspect of the planned work is too large to produce a satisfactory safety assessment, it may be appropriate to establish ‘hold points’ in the project, at which further progress is conditional on securing the further necessary information. This can take a number of forms such as intrusive examination or research on material behaviour.

3.6.2. Comparison of assessment results with relevant safety criteria

A prime objective of the safety assessment is to demonstrate that the potential hazards arising from decommissioning have been identified, consequences estimated and adequate measures proposed to ensure safety. This includes demonstrating that (i) appropriate hazard management strategies have been selected that eliminate hazards wherever practicable and (ii) adequate safety control measures have been identified to support delivery of the chosen decommissioning strategy. In doing so, it should be shown that relevant safety principles and criteria will be met.

Arguments for the sufficiency of safety control measures should preferably be deterministically based. Where it is not feasible or reasonably practicable to eliminate hazards from decommissioning operations, it should be shown that the radiological exposures arising from planned decommissioning activities are in line with the ALARA principle. Safety criteria may require the effects on people on-site and off-site to be evaluated, and typically, include the following:

— Dose limits to workers;
— Limits on radioactive discharges from liquid or aerial releases;
— Dose limits to the critical group;
— Limits on concentrations of chemotoxic substances.

Most importantly, the safety assessment should demonstrate that safety control measures are robust. There is a preferred hierarchy of controls with engineered lines of defence being preferable to procedural controls, though it is normal to use both (see Fig. 6). PPE should generally not be claimed as a line

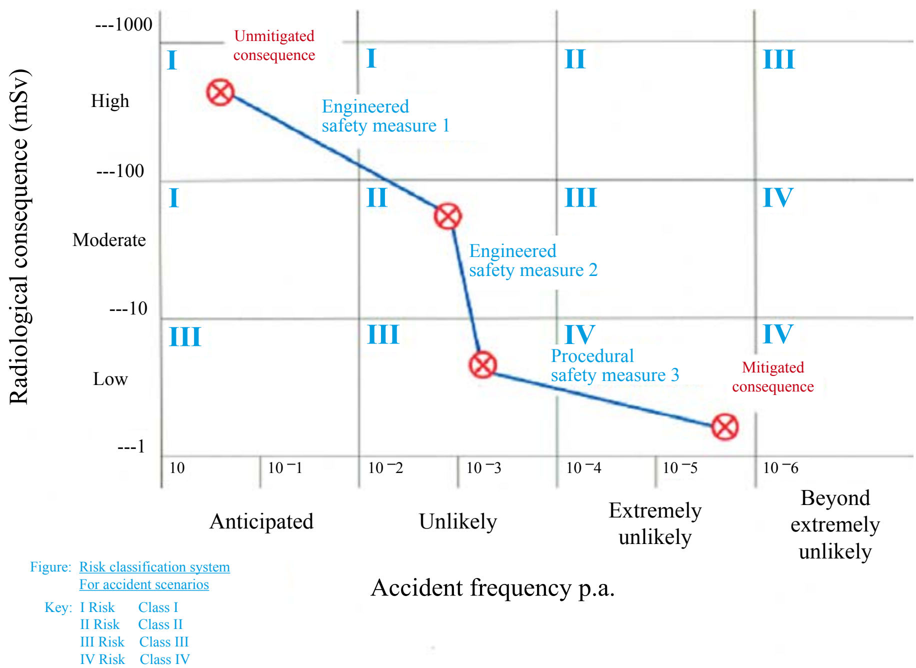


FIG. 6. Control measures and their combination to reduce exposure and/or risk.

of defence for accident mitigation. If PPE use is required, it will normally be specified as an output from the task based assessment (Fig. 6). The overall safety assessment is considered to be optional when no further safety improvements can be justified on ALARA grounds.

A diagrammatic example of the way in which appropriately selected safety control measures can reduce the risk is shown in Fig. 6.

Decommissioning work is often carried out on historic facilities that do not meet modern safety or design standards and require one-off or limited duration tasks. As a result, it is sometimes necessary to accept a temporary increase in risk and to utilize more stringent procedure based controls for such tasks. A typical example would be to adopt manual operations under management supervision for a discrete task, rather than remote handling — on the basis that the increased short term doses provide for future dose saving.

Some operators have developed safety standards based on their own national safety criteria that categorize facilities and their operations on the basis of the consequence of the most severe credible accident sequence. One such approach is to allocate facilities into the following categories — based on the outcome of a safety assessment (shown in more detail in Appendix XIII):

(a) Potential for significant off-site consequences (risk class I);
(b) Potential for only significant on-site consequences (risk class II);
(c) Potential for only significant within facility consequences (risk class III);
(d) Potential for only significant consequences at the work location (risk class IV).

Such a categorization system can be put to a number of uses, many of which support a graded approach to the safety assessment. For example, regulatory assessment, internal independent review and safety controls need to be proportionate to the facility categorization.

3.6.3. Safety control measures

A facility to be decommissioned will have safety control measures that were established for its operational phase. These should be reviewed to determine their relevance or otherwise, in the first non-operational phase, for example, care and maintenance and post-operational clean out, ahead of invasive decommissioning activities. Those that have no relevance to the non-operational phase should be removed. As described above, decommissioning activities will be subject to further control measures whose purpose is to ensure that work is conducted within a defined safe decommissioning working envelope. These controls can take the form of ‘engineered control measures’, such as the requirement to have an active ventilation system in operation to provide a pressure depression at the work-place so that no outward leakage of activity can take place, other than through a filtered discharge. It is normal to demonstrate the integrity of engineered control measures through a routine maintenance, inspection and test programme that is sometimes termed the surveillance programme. The requirement to have such a programme is often a fundamental requirement within a nuclear site's safety management programme. The establishment and evaluation of engineered control measures is a specialist subject, normally requiring engineering specialists and operators to assess the effectiveness of the specified control measures against the requirements specified by the safety assessor.

The other type of control is termed 'procedural control measures'. In some circumstances, only procedural controls will be possible, but in general, they must not be used as a substitute for engineered control measures, as the latter are more effective and less easily disabled by human error. An example of a procedural control measure related to the active ventilation system control discussed above could be a requirement to ensure that a specified number of fans are running and that the required pressure depression has been achieved before commencing work.

There are three types of control measures that will normally apply to work on a facility, and which apply equally to decommissioning and operational activities:

(a) A general control measure arising from the site operator safety management programmes: for example, the requirement to comply with specific legal and regulatory requirements can be met through the operators. An example is restrictions on working at heights.
(b) Specific control measures arising from the nuclear safety assessment of the planned decommissioning work: The use of an active ventilation system as described above provides an example of both an engineered and a procedural control. In some Member States, a 'graded approach' is taken to categorizing such controls, depending on their importance in controlling radiological exposure. The controls arising from the safety assessment are typically called the 'limits and conditions' for safe operation, with both engineered and procedural controls being documented. Procedural controls are often called operating instructions, and the engineered controls are supported by equivalent instructions.
(c) The third type of control measure results from task specific safety assessment of WPs. This was also discussed in Section 2.5 to show how radiological and conventional hazards controls can be integrated, and Section 7 describes how an operator's 'work control process' can be used effectively to ensure that all planned work can be conducted safely.

Examples of controls arising from a task specific safety assessment could be:

(i) Restrictions on time spent at the work-place specified by a radiological safety advisor;
(ii) The use of PPE;
(iii) The need for an approved lifting plan;
(iv) The need for isolation permits before work can commence;
(v) A requirement for the supervisor to brief the work team on the controls and any other restrictions that apply to the planned work.

Owing to changing hazardous substance inventories, uncertainties and new data from decommissioning activities, safety control measures can be expected to change throughout the decommissioning process, which is a key reason for decommissioning work to be broken down into stages, within which there are a number of defined WPs. The safety controls at each phase of work could differ, though not those from the operator’s safety management programme, which apply to all work. The controls arising from the safety assessment change as work progresses, and, in such circumstances, it is important that the operator puts in place sound arrangements for revising the control measures required for safe working. These changes can range from modifying or eliminating existing control measures to implementing new, more restrictive or modified ones.

Control measures arising from task specific safety assessments will be established separately on an ongoing basis, as each WP request is subject to safety assessment. Changes to the control measures as work progresses through the planned phases could include:

— Criticality controls;
— Surveillance programme requirements;
— Changed requirements for active ventilation system configuration;
— Requirements for remote, semi-remote or manual operations;
— Revised instructions for response to alarms and indications;
— Requirements for withdrawal from the work location in the event of loss of certain services;
— Revised emergency response requirements;
— Requirements for activity and discharge monitoring;
— Requirements for fire protection systems or alarms.

The safety assessment must include a clear discussion on the derivation of the safety control measures established to provide a safe working envelope, so that the measures can be seen to be suitable and sufficient.

The selection of the safety control measures should address the remaining phases of decommissioning of the facility up to its release from regulatory control. The controls are related to specific hazards and facility conditions identified in the safety assessment, and these should remain in force until the accident scenarios that require the control are no longer valid. The safety assessment demonstrates the conditions that must apply for specific control measures to be withdrawn. It is important to ensure that safety controls are not retired prematurely, and clearly, the independent review of the safety assessment is important in this regard. Such a situation could compromise worker, public and environmental protection; for example, criticality controls can be withdrawn once all significant amounts of fissile material have been removed.

The safety assessment should also include an explanation of the safety functions and their reliance upon specific parameters. For example, if active ventilation is required, the parameters may include differential pressure and filter efficiency. The method and period of surveillance should also be specified if it could affect the conclusions of the safety assessment.

By the very nature of decommissioning, facility systems will be removed. Some balancing is required to determine when engineered controls can be removed or replaced by administrative controls, and again for when administrative controls can be removed. The following criteria can be used when determining whether it is appropriate to retire a control:

— The hazardous condition being controlled is no longer present;
— The hazardous substance's physical form has changed to a less dispersible form;
— The amounts of hazardous substance are no longer of concern.

As stated above, in general, engineered safety features are considered preferable to administrative controls. However, it is expected that there will be less reliance on engineered systems and facility design features, and more reliance on administrative controls as the project progresses and as the accident potential of the decommissioning operation becomes smaller. For example, the operational limits and level alarms imposed on a processing vessel to prevent a release of hazardous substance are no longer valid if the material has been removed.

If unanticipated conditions arise, it will be necessary to review the adequacy of controls, and possibly to consider reintroducing previously retired controls. For example, if previously unidentified dispersible radiological materials were discovered, controls to prevent exposure and ingestion and inhalation would be required.

In many decommissioning projects, a point is reached where the hazard potential has been reduced sufficiently that no control measures from the safety assessment are required, and so the operator's safety management programme and the task specific safety assessment become the only necessary safety control measures. The point at which the safety management programme can be relied on is partly a matter for professional judgement, and is also dependent on the maturity and rigour of the safety management programme; it may also be indicated by the accident risk classification system described earlier.

The above discussion has identified three types of safety control measure that will each play a part in a decommissioning project. They are complementary, particularly when the hazard potential is high, and even when the hazard potential becomes more modest, it is still important to the safety of workers that the site's safety management programme is in place, and that each WP is subject to task specific safety assessment. Table 2 summarizes the role of the three types of procedural control.

The most important output from a safety assessment is the engineered and administrative safety control measures necessary to ensure the safety of the public and workers. It follows that the effective implementation of the identified control measures in both task and facility procedures and within the facility surveillance programme is a key aspect of effective safety management of decommissioning activities. As decommissioning proceeds through its planned stages, the control measures will be subject to change and, therefore, it is important that an effective process is in place for the change management of safety assessments and their resulting safety control measures.

TABLE 2. TYPES OF PROCEDURAL SAFETY CONTROL

	Degree of specificity of administrative controls		
	General	More specific	Very specific
Nature of administrative control	Compliance with site safety management programme	Limits and conditions for safe operation arising from nuclear safety assessment	Safety controls resulting from task specific safety assessment
When to apply the administrative control	For all work whether hazards are radiological or only conventional in nature	While the nuclear hazard potential requires 'limits and conditions' for safe operation	For all work whether hazards are radiological or only conventional in nature
Level of importance of administrative control	Important for legal and regulatory compliance to ensure general safety of workforce	Important for controlling nuclear and radiological hazards identified in safety assessment	Important for legal and regulatory compliance to ensure safety of workforce on specific tasks

3.7. APPLICATION OF SAFETY ASSESSMENT METHODOLOGY

A demonstration of the application of the DeSa safety assessment methodology described above is presented in Annex I. Three test cases are presented based on actual decommissioning projects, but with the safety assessment conducted within the framework of the described safety assessment process. The test cases are a nuclear power plant, a research reactor and a nuclear laboratory. These provide examples of the application of the methodology to a representative range of decommissioning projects.

4. GRADED APPROACH

4.1. INTRODUCTION

As outlined in Section 2.4, the term 'graded approach' refers to the level of detail of safety assessment that is appropriate when considering the risk presented from planned activities and accident scenarios required to be assessed. Detailed recommendations on the application of a graded approach to the safety assessment of decommissioning are provided in Annex II. The objective of a graded approach is to select a level of safety assessment commensurate with the risks determined from the preliminary safety assessment. Site operators should agree their risk methodology with their regulatory bodies. In addition to risk classification, it is recommended that the analysis be kept as simple as possible, commensurate with demonstrating compliance with objectives and criteria. Only if the result obtained using simple approaches fails to meet the relevant criterion (e.g. dose limit/constraint, risk level, frequency of occurrence), should a more complex approach be chosen.

The following sections outline how a graded approach may be applied to the various parts of a safety assessment.

4.2. LEVEL OF DETAIL FOR SAFETY ASSESSMENTS AND DOCUMENTATION

The level of analysis effort to be expended is based on a consideration of consequence and likelihood. This is shown in Table 3.

The risk classification system can be consequence based, i.e. determined by an assessment of unmitigated dose. The safety assessment will then take account of the mitigating effects of engineered and procedural safety measures.

TABLE 3. GUIDANCE ON THE LEVEL OF DETAIL OF ASSESSMENT REQUIRED

Radiological consequences	Likelihood			
	Beyond extremely unlikely	Extremely unlikely	Unlikely	Anticipated
Off-site				
On-site				
Localized in the facility				
Confined to the work area				

Note: The meanings of the shaded regions are:

Low consequence/low likelihood activity — only preliminary safety assessment required;

Intermediate consequence/intermediate likelihood activity — safety assessment required;

High consequence/high likelihood activity — detailed safety assessment required.

It is good practice in adopting a graded approach to assign a safety category to decommissioning activities on nuclear and other facilities based on the highest risk class identified (see Appendices XI and XIII). Analysing the consequences of events that might happen during an operation requires an understanding of the likelihood of this event happening and also evaluation of its consequence to workers or the public. The likelihood can be termed ‘anticipated’, ‘unlikely’, ‘extremely unlikely’ and ‘beyond extremely unlikely’, as shown in Appendix XI. The highest safety class arises from accidents that have the potential to result in significant radiation exposure to members of the public off-site. The control measures that are put in place to prevent or mitigate the consequences of such an accident should be commensurate with the potential consequences and likelihood. The essential basis of the classification system in Appendix XI is:

(a) Class I Potential for significant off-site exposure;
(b) Class II Potential for significant on-site exposure;
(c) Class III Potential for exposure only within the facility;
(d) Class IV Potential for exposure only within the work area.

An example of the connection between such categories and the dose ranges for the various consequences is provided in Appendix XIII.

The purpose of classification is to grade the safety of decommissioning activities, so that safety controls can be identified and implemented that are commensurate with their safety significance. Table 3 can be used for reference to the supporting definitions and procedures to determine the level of detail that should be performed (Appendix XI).

In some countries, the safety category of decommissioning activities is also used to determine the level of safety assessment and the approval route for safety assessments. An example of a classification system that can be used to determine the level of safety assessment required and a review and approval route for safety assessments is shown in Appendices XI and XIII.

4.3. GRADED APPROACH IN RADIOLOGICAL CHARACTERIZATION AND DATA ACQUISITION

Radiological characterization is one of the initial steps in the decommissioning process to obtain the data necessary for planning a decommissioning programme. A graded approach can be used in all of the phases of the planning and implementation of the radiological characterization of a facility in order to ensure adequate characterization without performing unnecessary work [82].

A graded approach can be applied to the following steps of a characterization programme:

(a) Review of historical documents and records: These provide information about the facility design, construction, operation, maintenance and non-routine shutdown, with a special emphasis on events with radiological consequences. A graded approach can be applied in order to optimize review efforts. The data collected in this process, including the results of previous surveys and measurements during the operational and the transition phase, facilitate subsequent analyses. By identifying the list of possible contaminants from a review of the facility history, the characterization effort can be optimized; the scope of the measurement programme can be limited, thereby saving time and money spent in unnecessary characterization.

(b) Calculation of activation: In cases where activation is significant, calculation methods for its assessment may be necessary. Methods for estimating neutron induced activity in a reactor core, its components and its surrounding structures involve the use of computer codes. For large power reactors, a full range of calculations may be needed, whereas for smaller research reactors, simplified models can be used, with the results confirmed by sampling and local measurements, and by comparison with similar reactors.

(c) Preparation of the sampling and measurement/analysis plan: In order to reduce characterization costs, different statistical techniques can be used to obtain information about an area or component from the results of a limited number of samples. A graded approach may be applied in order to restrict data gathering to the minimum commensurate with the need. For example, a simple statistical test or single measurements may be sufficient when this information is adequate for the purpose. A graded approach can also be applied in the development of the management system specifications. For example, if the characterization results indicate that decommissioning could have regulatory or health and safety implications, the samples must be subject to high management system standards. In contrast, if the results suggest minimal health and safety or regulatory implications, and if the results are only used to confirm existing radiological data, management system requirements could be less stringent.
(d) Performing direct measurements, sampling and laboratory analyses: This process can be expensive and difficult for highly activated components, as well as for 'hard to measure' radionuclides such as alpha emitters. A graded approach can help reduce personnel exposures and costs during the implementation of the sampling plan. The radiological measurements and samples are usually collected based on a grid system that is prepared for the area. Grid spacing can be varied depending on the needs of the survey and as a result of optimization. Grid size can be increased for areas that have a low potential for contamination.
(e) Determining the scope of the analysis: In order to reduce effort and costs, the nuclides to be analysed should be limited to those that are radiologically significant. A special effort should be made to reduce the number of analyses of 'hard to detect' radionuclides since these are usually the most costly. Appropriate methods based on correlation and scaling factors are normally used for this purpose [82].

4.4. GRADED APPROACH IN PERFORMING SAFETY ASSESSMENT

4.4.1. Screening and grouping of hazards

After the results of the radiological characterization have been obtained, the safety assessment can be planned. As pointed out in Section 3.3, it is advisable to first identify the hazards and then to perform a screening assessment in order to identify the relevant scenarios and to omit those with low consequences. Existing analyses, for example, from the operational phase, may be of help, and should be reviewed in this process.

The selection of relevant scenarios for inclusion in the safety assessment depends on the hazard potential of the facility and the work planned. It might be necessary to analyse only one or a few scenarios in the case of small facilities, while it may be expected that a larger number of scenarios would be needed for nuclear power plants or larger fuel cycle facilities. Depending on the similarities between these scenarios, they may be grouped and/or replaced by an enveloping scenario, so that the number of different scenarios for which calculations have to be performed can be further reduced.

4.4.2. Complexity of approaches and calculation methods

The complexity of the safety assessment and approaches for calculation will depend on:

— Scenarios leading to releases of radionuclides during normal operation and from accidents;
— The source term of such releases;
— The dispersion in the environment via water and airborne pathways;
— The level of dose from ingestion, inhalation and external irradiation caused by such releases;
— The level of dose due to external irradiation from the facility itself.

With reference to the categorization of Section 4.2, especially Table 3, the following observations can be made:

— The level of detail at which accident scenarios have to be developed and analysed increases with the hazard potential of the facility or the planned work, respectively. For facilities/work falling into classes I and II, several accident scenarios might have to be analysed, while for classes III and IV, the preliminary safety assessment is normally sufficient. For class I, it might be necessary to perform a partly probabilistic analysis of the accident scenarios in order to establish a proper ranking.
— The determination of the source term for releases of radionuclides from the plant as a consequence of normal operation or accident situations requires a higher effort for facilities/work falling into class I. For classes III and IV, conservative assumptions in the preliminary assessment should suffice.
— The calculation of dispersion and, consequently, of doses may need detailed models for classes I and II to achieve sufficient accuracy when potential radiation doses are significant. Enveloping assumptions and the use of simple models usually suffice for classes III and IV.

— The extent to which site specific information and data have to be used to supplement and verify model predictions also depends on the potential hazards presented by the decommissioning task. The need for site specific information and adaptation of computer models usually increases going from class IV to class I.

4.4.3. Alternative approaches

As an alternative to performing a complete and detailed safety assessment, other methods may be used. For example, the use of predefined concentrations of radionuclides in liquid and/or gaseous releases may be used; the concentrations are determined in such a way that, if complied with, the associated dose constraint or dose limit will never be exceeded. Another approach could be to draw on positive experience gained from similar work at a similar facility. This means that the relevant parts of the safety assessment performed at other facilities of the same type could be transferred to the work in question.

4.5. GRADED APPROACH IN THE INDEPENDENT REVIEW PROCESS

The independent reviewer must decide whether the safety assessment provides an adequate demonstration that the consequences for the public and the workers are below prescribed limits or constraints, both during normal operation and as a result of accidents during decommissioning. The reviewer must also be able to conclude that the safety assessment is accurate and covers the proposed scope of decommissioning work. A relevant part of the reviewer’s task is the verification of the assumptions and data on which the safety assessment has been based.

Independent reviews can be graded in the same way as other activities; for example, decommissioning that poses only very low hazards will require less effort for verification of the assumptions, data and calculations used than decommissioning projects that could result in significant impacts.

5. CONFIDENCE BUILDING IN SAFETY ASSESSMENT

It is necessary to be able to demonstrate a high degree of confidence in the quality of the process and in the people involved in the preparation, review and approval of the safety assessment. Stakeholders who need to gain confidence in the safety assessment include:

— The regulatory body, which has to be convinced of the completeness and robustness of the safety assessment. Regulatory bodies may have their own internal review procedures, and they normally require formal review and approval of all or parts of the safety assessment. (A detailed evaluation of the regulatory review process can be found in Annex III of this report.)
— National governmental organizations (who often own the facilities), local authorities, the environmental regulator and political representatives of the local population.
— Other persons within the operator's organization, such as internal safety committees and the decommissioning project manager, who is the prime customer for the safety assessment.

The principal means by which confidence in the soundness and quality of safety assessments are ensured are discussed below.

5.1. MANAGEMENT SYSTEM

It is normal for nuclear site operators, in common with any significant public or commercial organization, to have a documented management system that specifies the organization structure, its policy, and the responsibilities and functions of the organization's management. The management system includes:

— Clear organizational structure and responsibilities;
— Competency and training requirements;
— The requirement for approved standards, procedures and guidance to cover the organization's tasks;
— Instructions to cover specific tasks and activities;
— The requirement for quality assurance audits of its processes to demonstrate their adequacy and that they are being complied with.

The requirements of an organization seeking certification in this field are specified in such standards as ISO 9001 of the International Organization for Standardization, and guidance on their application to nuclear facilities can be found in Refs [83–86].

It is important to note that nowadays the descriptor for such a system is usually 'management system', though earlier, it was more commonly called a 'quality management system'. The safety management programme discussed in this report is a subset of an organization's management system.

The management system of an operator will contain policy and procedures covering the production and procurement of technical services that will include safety assessment production, its independent review and the approval of decommissioning activities and other safety related activities.

The key organizational management system requirements for the production of good quality safety assessments are summarized below:

- The facility operator must have a documented management system that specifies organizational responsibilities for the production of safety assessments and the competencies required of the relevant staff, including the capability to act as an 'informed customer' in the procurement of safety assessment from contracting organizations.
- The organization should ideally have its own relevant policy, standards and procedures with regard to methodologies, as well as recommended calculation and analysis methods, codes and the recommended data necessary for the execution of safety assessments; it should either have an internal competency or be competent to procure these services [87–89].
- The organization should have procedures for the production, independent review and approval of safety assessments and supporting documentation.
- A complex safety assessment should be treated as a project, with team members appointed according to their experience and areas of expertise. Accordingly, the management system should specify the requirements for establishing a project, such as project plans, a programme, specification and the formal appointment of team members.
- A procedure is normally established for defining the requirements for independent internal review. It will require that its formal obligations and interface with the national regulatory body are included within the management system. Independent review involves safety professionals, independent of the decommissioning project, conducting a detailed review of the safety and related engineering assessment. There can be a requirement for an internal management committee to provide assurance that proper procedures have been followed, and this also needs to be included in the management system. In some Member States, the highest category of safety assessments is required to be considered by a safety committee, which has members independent of the operator's organization. The person(s) assigned to such committees must be suitably qualified and experienced, so that they can properly execute their duties.
- There may also be a requirement in some organizations to maintain records of staff and technical support contractors involved in safety assessment production and review, so that their competency and qualifications to undertake such work can be demonstrated. They may also be required to record their standard of performance on earlier safety assessment work.

— An overarching requirement of any organization's management system is that it is subject to a programme of quality assurance audits to demonstrate that it is robust and to identify any necessary corrective actions in the event that non-conformances with the system's requirements are found. Lead management system auditors normally require national accreditation, and if the organization seeks formal management system certification for its management system, it will require being subjected to external audit for this purpose. Additional guidance on many of the relevant aspects of quality assurance programmes can be found in Refs [83–86].

5.2. INDEPENDENT REVIEW AND APPROVAL PROCESS

Some aspects of independent reviews were discussed above in the context of site operator management systems. More specifically, a key part of the confidence building process in the safety assessment is the conduct of an independent review of the safety assessment. The independent review should be performed by persons without direct responsibilities for the specific decommissioning project. The reviewer(s) might be internal or external to the operator organization, but the reporting route into the organization must be independent of the decommissioning project. An independent review may be performed interactively during the preparation of the safety assessment or following its completion. It is normal for the extent of independent reviews to be commensurate with the risks presented by the proposed activities. A simple accident risk based classification system is described in Appendix XI to assist in such classification. Those facilities with a significant off-site risk potential would be subject to a detailed independent review, and normally a regulatory review before approval to proceed is required.

A suitably qualified and experienced person(s), organizationally independent of the decommissioning project, is normally appointed to conduct or manage the independent review. It is important that the review be undertaken in a logical and systematic manner with clear acceptance criteria and that the approach, findings, recommendations and other communications with the safety assessment team are properly documented. The independent reviewer (or review team, if it is a large and complex safety assessment) may need to bring in other specialists for support in areas where the reviewer does not have sufficient expertise. This could well be the case for engineering assessments of SSCs and specialist subjects, such as seismic assessment, where engineering specialists may need to be involved.

When there has been sufficient iteration between the safety assessment team and the independent reviewer(s), and they have agreed on the significant issues that arose from the assessment and on how these and any recommendations are to be resolved, the report is finalized and submitted for formal approval prior to work being allowed to commence. If the regulatory body is part of the approval process, it is normal for the independent reviewer’s report to be sent to the regulatory body, together with the safety assessment report when seeking formal approval to proceed.

6. REVIEW AND UPDATE OF SAFETY ASSESSMENTS DURING THE DECOMMISSIONING PROCESS

The independent review and regulatory review processes have been discussed in previous sections. There may be circumstances in which a review and update of a safety assessment is required during decommissioning. The requirement could arise if assumptions and data significant to the safety assessment were found to be invalid during decommissioning. For example, this could be due to higher than expected radiation levels that could require a change to work methods and a revised safety assessment. In some Member States, the regulatory body requires a periodic review of site safety and of the extant safety assessments. In general, however, this is not a frequent requirement.

It is usual for the regulatory body to allow or require the licensee to implement an ‘internal change control system’ to allow the licensee the flexibility to document and authorize minor changes to safety assessments during decommissioning without having to revise and reissue the whole report for approval [88, 89]. Such a change control procedure also specifies the independent review and approval requirements of the change documentation; these are very similar to the requirements for safety assessment review and approval. A classification system can be used to specify the review and approval requirements based on the safety significance of the change proposal, which can include the requirement to seek approval from the regulatory body for higher category changes.

The type of change control procedure outlined above allows the operator an efficient means for taking into account changes in planned decommissioning activities, new data, experience, etc. that could affect safety. It can also be used to document changes in the state of the facility at any time.

During the performance of the decommissioning work, hazardous substances or facility physical conditions may be discovered that were not previously evident, and this may require further assessment. The change management procedure should be used to evaluate all proposed activities, changes and discoveries that may affect safety and are not part of the current safety assessment. As noted above, the change management procedure normally includes a mechanism for evaluating the significance of any change, the need for additional assessment and safety controls, the documentation affected or required by the change, and the approval and training requirements for implementing the change. The procedure could include a set of questions to aid classification, such as:

— Is there an unanalysed hazard, change or increase in uncertainty in analysed hazards or a change in hazardous substance type, form or quantity as a result of the proposed activity, or a discovery that could affect (directly or indirectly) the health and safety of workers at or around the job site?
— Are prescribed safety control measures adequate to protect the worker, as established by approved hazard baseline documentation, and have the safety controls been reviewed and approved?

In addition, it is appropriate that the change management procedure addresses hazardous substance inventory maintenance to ensure that the rigour of hazards analysis and associated safety controls are commensurate with the inventory changes. A change management methodology for screening and evaluation should be developed for the following types of change:

— Minor changes that affect job controls or instructions specified in work plans that need to be implemented with minimal review (e.g. typographical errors, administrative details or insignificant changes that have no potential to influence health and safety).
— Changes that affect the original work plans and require worker or facility safety evaluation, but do not require changes to existing safety assessment documentation (e.g. hazardous substances in amounts or locations different than assumed).
— Changes that affect the safety basis of a safety assessment and require changes to the current facility safety documentation or work permits (e.g. unanalysed hazards that require new analysis or safety controls or changes that affect performance of SSCs): A determination should be made as to whether the proposed work or changing facility conditions (as decommissioning activities proceed) will be within the safety basis defined in the facility's hazard baseline documentation.

Obtaining approval for and using such a process during a decommissioning project could allow the operator to proceed without the involvement of the regulatory body, provided that the changes to the planned decommissioning work do not affect the safety of decommissioning activities.

7. WORK CONTROL PROCESSES AND INDUSTRIAL SAFETY ASSESSMENT OF WORK PACKAGES

The use of a ‘work control process’ for the safety assessment of individual WPs and the specification of the required safety controls was discussed in Sections 2.5 (see Fig. 3) and 3.6.3. These described briefly how the safety control measures arising from a safety assessment are combined with the control measures identified from the assessment of industrial and other non-radiological hazards for individual WPs. In this way, decommissioning workers will only be allowed to start work once all necessary safety controls are in place, thus protecting them from all hazards, i.e. radiological and non-radiological hazards.

The work control process used to control decommissioning activities should be designed to ensure that personnel, including contractors, are properly protected from all hazards when conducting approved WPs and that they are able to conduct decommissioning operations in the specified manner. It is an important principle of safety management programmes that no invasive decommissioning work should take place in a facility without it being initiated as a formal ‘work request’ in accordance with the site’s work control procedure, which is part of an approved decommissioning programme. If the proposed work is not already covered by approved work instructions, the work request should be accompanied by a documented description of the work and the work methods to be undertaken. A task specific hazard assessment of the industrial and radiological hazards involved in this work would then be undertaken by competent persons, who are often part of the site’s work planning and work control arrangements.

Any control measures and other requirements needed to ensure a safe working environment should be specified in the documented WP provided to the workers. This could include the need for a ‘permit to work’, for example, if working on live systems that require isolation before work can proceed. System isolations should involve the use of locking systems to ensure isolations cannot be interfered with. Other specified requirements for work could be the use of PPE, a pre-work brief by the work supervisor, work in airline suits or the use of safety harnesses.

It is also usual for radiation protection advisors at the site to provide advice to ensure occupational radiation exposures that may arise from planned work will be ALARA. Such advice is routed through the work control process and incorporated into the final documented WP. Consideration of accidental exposure and the resulting safety control measures identified within the safety assessment are also included.

These complementary processes for the establishment of safety controls from the safety assessment and from the work control process increase the confidence that a suitable and sufficient safety assessment has been conducted, and that any hazards to the public and workers have been considered and appropriate safety controls put in place. A schematic representation of this safety assessment process was presented in Fig. 3.

8. SUMMARY AND LESSONS LEARNED

In this report, a flexible safety assessment methodology that can be applied to decommissioning of facilities using radioactive material has been presented. This meets one of the key requirements of the DeSa project, which is to develop a harmonized approach to safety assessment and to define the elements of safety assessment for decommissioning activities.

The methodology can be readily applied to almost all types of decommissioning project. Three test cases have been developed to demonstrate the application of the DeSa methodology (see Annex I). The test cases apply to a nuclear power plant, a research reactor and a nuclear laboratory. The objectives of safety assessment and the role of safety assessment within the overall decommissioning planning and execution processes are described. The rationale for carrying out safety assessment in phases and stages for large projects, and for safety assessment performance commensurate with the level of risk presented by the planned work (a graded approach) are discussed.

A detailed discussion, which provides an overview of the safety assessment process based on good international practice, is presented, so that the basis and derivation of the developed safety assessment framework and methodology are clear.

Decommissioning is an invasive process that presents industrial and chemical hazards as well as radiological ones, and indeed the non-radiological hazards generally represent the greater overall risk to workers. The report describes procedures that allow the effective control of all types of hazard during decommissioning work.

The various means of ensuring that safety assessments are accurate and of sufficient quality and depth are discussed. The operator's independent review of the safety assessment and the use of approved calculation methods and data by qualified and experienced persons are two important examples of how quality is ensured.

In the discussions, during the various DeSa meetings and working groups, there were many exchanges of experience between the representatives of Member States, and a consensus on the development of the DeSa safety assessment framework and methodology was established. From these discussions, many good practices and important lessons were identified. Some of the key lessons learned in the development of the DeSa methodology are listed:

— Using a standardized framework and a systematic step by step methodology in the production of safety assessments leads to improved consistency and a quality product. Assessment tools and techniques are available internationally to allow the effective use of the methodology.
— A deterministic approach to safety assessment and the identification of safety control measures is recommended as being effective in providing adequate protection for workers and the public during decommissioning activities.
— It is important that safety assessment documentation can be clearly understood by all of its users (stakeholders), and that the extent of assessment is commensurate with the safety significance of the decommissioning work. Many examples of good practice have been identified in what is called the graded approach to safety assessment. Classification of facilities, accident sequences, work activities and engineered systems are described, as these can be used to specify differing safety assessment requirements for higher safety classifications.
— For a multiphased project, it is generally good practice to carry out a preliminary safety assessment using simple and bounding calculations to address potential accident scenarios and radiation exposure during decommissioning work. This enables early classification, so that the safety assessment effort can be directed in proportion to safety significance and assist the effective grouping and screening out of accident scenarios.
— Decommissioning involves changing facility states, including the removal of engineered safety barriers. It is important to have effective processes for the review and revision of safety control measures as decommissioning proceeds.
— Decommissioning of large facilities may be conducted in a number of phases and/or stages in accordance with the decommissioning plan. It is generally good practice to produce separate safety assessments for different phases so that they are focused on current and near term activities and to avoid overly complex documentation. Decommissioning strategy and work methods may evolve during a decommissioning project, and so it is important that supporting safety assessments are kept in line with such project developments.
— The safety role of many engineered SSCs during decommissioning will differ significantly from their role during the operational phase of a facility. Some will be retired, new ones may be added and the functional requirements of others will change. Once spent fuel has been removed, its importance to safety will normally decrease. It is, therefore, important that the safety requirements of SSCs are identified and classified in terms of their safety significance, and that the extent of the engineering assessment is commensurate with the importance of the SSCs to safety.

Appendix I

GENERAL CONTENT OF A DECOMMISSIONING PLAN

Safety assessment is generally developed as part of a decommissioning plan (preliminary or final) and, therefore, should be based on and be consistent with the elements of this plan. The following list of elements of a decommissioning plan is based on Refs [3, 5, 10]. Not all of the elements in this list will be found in every decommissioning plan. In accordance with a graded approach, the level of detail will depend on the complexity of the decommissioning project.

1. INTRODUCTION

2. FACILITY DESCRIPTION

   2.1. Site location and description
      2.1.1. Population distribution
      2.1.2. Current/future land use
      2.1.3. Meteorology and climatology
      2.1.4. Geology and seismology
      2.1.5. Surface water hydrology
      2.1.6. Groundwater hydrology
      2.1.7. Natural resources
   2.2. Buildings and systems description
   2.3. Radiological status
      2.3.1. Contaminated structures
      2.3.2. Contaminated systems and equipment
      2.3.3. Surface soil contamination
      2.3.4. Subsurface soil contamination
      2.3.5. Surface water contamination
      2.3.6. Groundwater contamination
   2.4. Facility operating history
      2.4.1. Authorized decommissioning activities
      2.4.2. Licence or authorization history prior to decommissioning
      2.4.3. History of design or modifications of activities
      2.4.4. Spills and occurrences affecting decommissioning
      2.4.5. Previous decommissioning activities
      2.4.6. Prior on-site burial

3. DECOMMISSIONING STRATEGY

   3.1. Alternatives considered
   3.2. Rationale for chosen strategy
   3.3. Planned use of the facility and site during and after decommissioning

4. REGULATORY REQUIREMENTS

   4.1. Legal and regulatory requirements
   4.2. Radiological criteria during and after decommissioning
   4.2. Clearance criteria for buildings and material
   4.3. Final site release criteria

5. DECOMMISSIONING ACTIVITIES

   5.1. Contaminated structures
   5.2. Contaminated systems and equipment
   5.3. Soil
   5.4. Surface water and groundwater
   5.5. Decommissioning approach (phases)

6. AVAILABILITY OF SERVICES, ENGINEERING AND DECOMMISSIONING TECHNIQUES

   6.1. Decontamination
   6.2. Dismantling
   6.3. Waste management

7. WASTE MANAGEMENT

   7.1. Identification of waste streams
      7.1.1. Amount
      7.1.2. Types (solid, liquid and gaseous radioactive waste, waste containing both radioactive and other hazardous material)
      7.1.3. Location
      7.1.4. Calculation methods
   7.2. Waste management practices
      7.2.1. Criteria for segregating materials
      7.2.2. Proposed processing, handling, transport, storage and disposal methods

7.2.3. The potential to reuse and recycle materials, and related criteria; and anticipated discharges of radioactive and hazardous non-radioactive materials to the environment

8. COST ESTIMATE AND FUNDING MECHANISMS

8.1. Cost estimate
8.2. Sources and funding mechanisms

9. SAFETY ASSESSMENT

9.1. Safety assessment framework
9.2. Description of facility and decommissioning activities
9.3. Hazard analysis: identification and screening
9.4. Hazard analysis: evaluation
9.5. Evaluation of results and identification of controls

10. PROJECT MANAGEMENT

10.1. Project management approach
10.2. Project management organization and responsibilities
10.3. Task management organization and responsibilities
10.4. Safety culture
10.5. Experience and technical qualification requirements
10.6. Training
10.7. Special services and technology
10.8. Contractor support
10.9. Schedules
10.10. Radiation protection procedures
10.11. Exchange of experience of decommissioning operations

11. SURVEILLANCE AND MAINTENANCE

11.1. Equipment and systems requiring surveillance and maintenance
11.2. Schedule for surveillance and maintenance
11.3. Continued surveillance and institutional control (for deferred stages)

12. ENVIRONMENTAL ASSESSMENT

13. COMPLIANCE AND ENVIRONMENTAL MONITORING

13.1. On-site programme
13.2. Off-site programme
13.3. Monitoring for compliance with clearance values, criteria and end points

14. HEALTH AND SAFETY

14.1. Radiation protection plan
14.2. Nuclear criticality safety
14.3. Industrial health and safety plan
14.4. Dose estimation
14.5. Optimization analyses for major tasks and programme

15. QUALITY ASSURANCE

15.1. Structure of decommissioning organization
15.2. Quality assurance programme
15.3. Document control
15.4. Control of measuring and test equipment
15.5. Corrective actions
15.6. Quality assurance records
15.7. Audits and surveillance
15.8. Experience, resources and qualification of staff
15.9. Record keeping programme
15.10. Lessons learned programme

16. EMERGENCY PLANNING

16.1. Organization and responsibilities
16.2. Emergency situations
16.3. Records

17. PHYSICAL SECURITY AND SAFEGUARDS

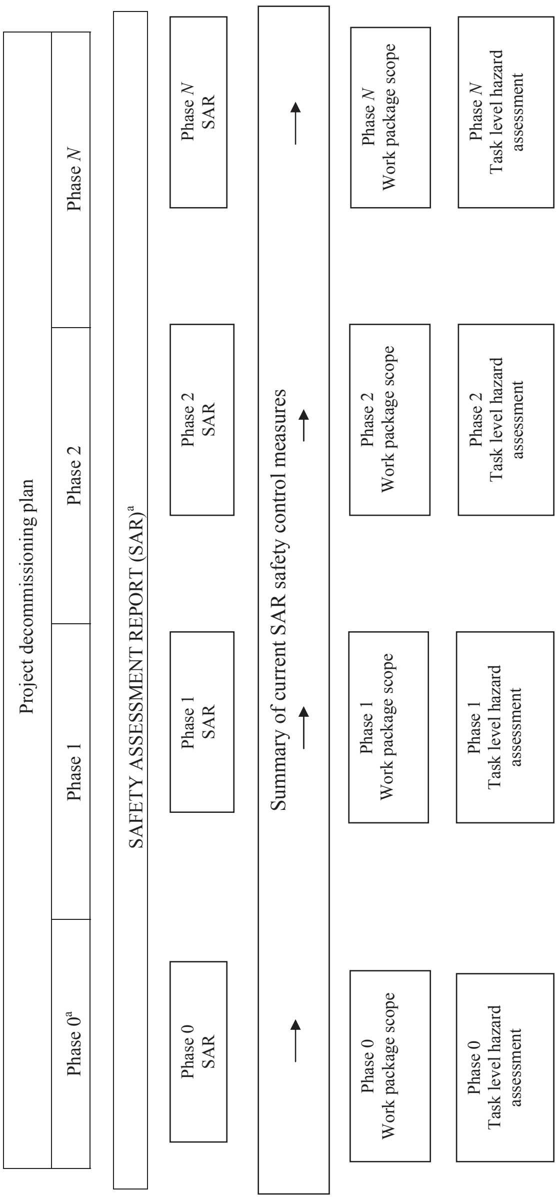
17.1. Organization and responsibilities
17.2. Physical security programme and measures
17.3. Safeguard programme and measures

18. FINAL RADIOLOGICAL SURVEY

19. STAKEHOLDER INVOLVEMENT

Appendix II

EXAMPLE OF A SAFETY DOCUMENTATION MODEL FOR A COMPLEX DECOMMISSIONING PROJECT



[a] Optional; may be of value for a high level case that includes a care and maintenance phase prior to dismantling.

Appendix III

ILLUSTRATION OF DECOMMISSIONING TASKS FOR DIFFERENT TYPES OF FACILITY

TABLE 4. URANIUM MINE AND MILL [87]

Planning phases		Work packages
Mine workings	(l)	Remove salvageable equipment and hazardous materials;
	(2)	Stabilize/fill underground workings/ open pits;
	(3)	Assess crown pillar stability;
	(4)	Seal shafts, raises, declines and portals;
	(5)	Remove head frame and hoists;
	(6)	Remove ancillary structures and services/ remediate contaminated soils;
	(7)	Grade and replant immediate area.
Mill site	(1)	Remove coarse ore in storage;
	(2)	Remove process chemicals and hazardous materials in storage;
	(3)	Remove contaminated equipment and vessels for disposal;
	(4)	Remove salvageable equipment and materials, decontaminate as needed;
	(5)	Demolish remaining structures and tanks;
	(6)	Remediate contaminated soils;
	(7)	Grade and revegetate immediate area.
Tailings management area	(1)	Construct/upgrade containment structures for long term;
	(2)	Construct/improve water drainage or diversion works;

TABLE 4. URANIUM MINE AND MILL [87] (cont.)

Planning phases	Work packages	
	(3)	Recontour tailings;
	(4)	Place final cover (soil, rock, water, etc.);
	(5)	Install/upgrade monitoring/treatment facilities;
	(6)	Remove pipelines, pumps and other ancillary structures;
	(7)	Grade and revegetate immediate area.
Waste rock management area	(1)	Stabilize with respect to infiltration/ acid generation;
	(2)	Recontour/grade and vegetate or relocate for disposal as required.
Hazardous material storage area	(1)	Remove materials inventory;
	(2)	Remove contaminated tanks and structures for disposal;
	(3)	Demolish remaining structures and tanks;
	(4)	Remediate contaminated soils;
	(5)	Grade and revegetate immediate area.
Effluent treatment	(1)	Remove remaining effluents and chemicals in storage;
	(2)	Remove unnecessary treatment plant, piping and other structures;
	(3)	Remediate mine water, sewage and other effluent treatment ponds and sludges;
	(4)	Grade and revegetate immediate area.

TABLE 5. URANIUM REFINING AND CONVERSION [87]

Planning phases	Work packages
Materials shipping, receiving and storage areas	(1) Remove product/yellow cake inventories; (2) Decontaminate and remove equipment, tools, conveyors, hoists, etc.;
Digester process area	(1) Remove contents and loose contamination from primary and secondary digesters; (2) Dismantle digester vessels; (3) Remove ancillary piping, valves and electrics; (4) Remove other equipment and tools.
Solvent extraction process area	(1) Remove contents of vessels and piping; (2) Decontaminate and dismantle feed tanks; (3) Decontaminate and dismantle column trains; (4) Decontaminate and dismantle settling tanks; (5) Dismantle ancillary piping, valves, electrical and conveyance systems.
Reactor areas	(1) Remove contents of denitrification reactors; (2) Decontaminate and dismantle reactor vessels; (3) Decontaminate and remove reaction gas scrubber system; (4) Remove active drains.
Effluent management systems	(1) Remove contents of effluent neutralization vessels; (2) Remediate effluent monitoring and treatment lagoons;

TABLE 5. URANIUM REFINING AND CONVERSION [87] (cont.)

Planning phases	Work packages	
	(3)	Remediate storm water management lagoon;
	(4)	Remove final effluent discharge line;
	(5)	Decontaminate sumps;
	(6)	Decontaminate and remove raffinate evaporators;
	(7)	Decontaminate and remove liquor evaporators.
Emission control system	(1)	Remove baghouse filter system;
	(2)	Remove central vacuum system.
Solid waste management areas	(1)	Decontaminate uranium scrap area;
	(2)	Decontaminate and remove refuse incinerator;
	(3)	Decontaminate drum cleaning and processing area;
	(4)	Remove inventory and decontaminate low level storage area.
Maintenance and trade shops	(1)	Remove tools and equipment;
	(2)	Remove other materials and stores;
	(3)	Remove work benches, furniture, etc.;
	(4)	Dismantle mechanical and electrical rooms;
Administrative offices and laboratories	(1)	Remove equipment, furniture and fixtures;
	(2)	Decontaminate laboratories and remove equipment.

TABLE 5. URANIUM REFINING AND CONVERSION [87] (cont.)

Planning phases		Work packages
Chemical tank farm	(1)	Remove inventory;
	(2)	Dismantle and dispose of tanks.
Building surfaces and structure	(1)	Decontaminate interior floors, walls and ceilings as required;
	(2)	Decontaminate exterior surfaces as required;
	(3)	Remove heating, ventilation and air conditioning ductwork;
	(4)	Remove plumbing, electrical and other services;
	(5)	Demolish structures.
Site	(1)	Remove waste piles and other potentially contaminated materials;
	(2)	Remove contaminated soil and asphalt;
	(3)	Grade and revegetate immediate area;
	(4)	Final release survey.

TABLE 6. POOL TYPE RESEARCH REACTOR [87]

Planning phases		Work packages
Reactor building/room	(1)	Remove control/absorber rods and drive assembly;
	(2)	Remove core components;
	(3)	Remove experimental sites/equipment;
	(4)	Remove primary heat exchangers and piping;
	(5)	Dismantle secondary cooling system;
	(6)	Drain pool water;
	(7)	Remove pool liner;
	(8)	Dismantle pool walls;
	(9)	Dismantle water purification system;
	(10)	Remove fuel and fuel storage equipment;
	(11)	Remove control room equipment;
	(12)	Remove ventilation system;
	(13)	Remove water, electrical, sewer and other services;
	(14)	Dismantle cranes and hoists;
	(15)	Dismantle structure.
Hot cells and laboratories	(1)	Remove equipment and supplies;
	(2)	Remove active drains;
	(3)	Remove fume hoods and breathing air ventilation;
	(4)	Dismantle hot cells;
	(5)	Remove water, electrical, sewer and other services;
	(6)	Dismantle structures.

TABLE 6. POOL TYPE RESEARCH REACTOR [87] (cont.)

Planning phases		Work packages
Ancillary buildings	(1)	Remove equipment, tools and supplies;
	(2)	Remove water, electrical, air and sewer services;
	(3)	Dismantle structures.
Site	(1)	Grade and revegetate immediate area;
	(2)	Final survey.

TABLE 7. CANDU NUCLEAR POWER PLANT [87]

Planning phases	Work packages
Calandria vault	(1) Dismantle calandria internals and shells; (2) Decontaminate vault; (3) Segment and remove calandria vault.
Reactor building	(l) Remove steam generators; (2) Remove primary heat transport pumps and piping; (3) Remove moderator dump tanks; (4) Dismantle and remove emergency core cooling system; (5) Remove fuelling machine and ducts; (6) Dismantle and remove internal concrete structures and shielding; (7) Remove steel walkways, ladders and stairs; (8) Dismantle containment structures and floor slab.
Vacuum building and ducts	(1) Dismantle structures (decontaminate as necessary).
Reactor auxiliary bay	(1) Remove inventory of irradiated fuel; (2) Drain and decontaminate bays; (3) Segment and remove bays; (4) Remove control centre equipment; (5) Remove standby generators; (6) Demolish structure.
Turbine hall	(1) Remove turbine generators; (2) Remove other electrical and ancillary equipment; (3) Demolish structure.

TABLE 7. CANDU NUCLEAR POWER PLANT [87] (cont.)

Planning phases	Work packages
Turbine auxiliary bay	(1) Remove condenser; (2) Remove condenser water circulating and service pumps/piping; (3) Remove de-aerator; (4) Remove feedwater heaters, piping and other equipment; (5) Raise structure.
Service buildings	(1) Remove inventory of liquid and solid wastes; (2) Decontaminate, dismantle and remove waste management equipment; (3) Remove equipment from and decontaminate maintenance shops; (4) Remove equipment from and decontaminate laboratories; (5) Remove other equipment and materials from stores; (6) Demolish structure.
Heavy water treatment and storage facility	(1) Remove inventory of heavy water; (2) Remove other equipment and materials; (3) Decontaminate and dismantle structures.
Water treatment system	(1) Remove pumphouse; (2) Remove water treatment equipment; (3) Dismantle structures.
Administration building	(1) Remove contents; (2) Dismantle structures.

TABLE 7. CANDU NUCLEAR POWER PLANT [87] (cont.)

Planning phases	Work packages
Site	(1) Remove services, roads, etc.;
	(2) Final radiological and contaminants survey;
	(3) Grade and landscape.

Appendix IV

EXAMPLE OF A GRADED APPROACH TO ASPECTS OF DECOMMISSIONING OTHER THAN SAFETY ASSESSMENT

Level of review	**Limited review**		**Limited review with decommissioning plan**	**Review with special expertise**	**Restricted release or alternate criteria**
Description	Sealed source, screening criteria	Screening criteria, no decommissioning plan	Screening criteria with decommissioning plan	Site specific, potential groundwater contamination with decommissioning plan	Restricted release or alternate criteria with decommissioning plan
Environmental compliance	No action required	Environmental assessment	Environmental assessment	Environmental assessment	Environmental impact statement
Licensee requests release for restricted or unrestricted use	Unrestricted use	Unrestricted use	Unrestricted use	Unrestricted use	Restricted use
Decommissioning plan review documentation	Not applicable	Not applicable	Letter to the licensee	Safety evaluation report	Safety evaluation report
Method for demonstrating site is suitable for release	Survey or demonstration	Survey or demonstration	Survey or demonstration	Site specific	Site specific
Confirmatory or split sample survey	Not common	Depends on licensee's survey and radioactive material use at facility	Depends on licensee's survey and radioactive material use at facility	Yes	Yes
Closeout inspection	No	As appropriate	As appropriate	Yes	Yes
Public notice of action	No	Yes — announce finding of no significant impact	Yes — (1) announce decommissioning plan receipt and regulator's intended actions and (2) announce finding of no significant impact	Yes — (1) announce decommissioning plan receipt and regulator's intended actions and (2) announce finding of no significant impact	Yes — (1) announce decommissioning plan receipt and regulator's intended actions and (2) announce environmental impact statement

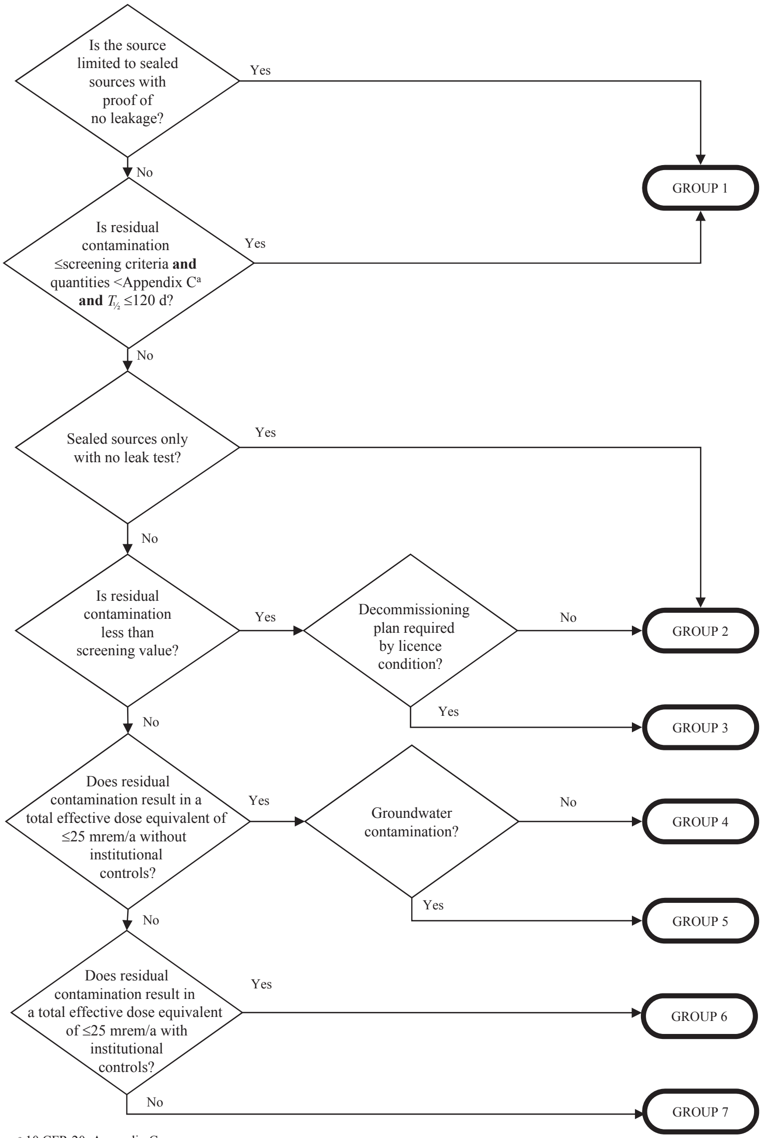
The form and level of the remaining radioactive material determines the actions required in the decommissioning of a facility and the level of documentation required to demonstrate decisions and completed actions.

For example, if a facility only has sealed sources with proof that there has been no leakage or that leakage is below regulatory thresholds, limited action is required. There is no need for environmental assessment, a decommissioning plan, use restrictions or verification of completion by confirmatory survey or sampling. This is in contrast to a facility at which some level of radioactive material remains, requiring restrictions on future use. For this type of facility, environmental compliance must be demonstrated through a rigorous assessment method, and decommissioning actions must be planned and formally accepted by the regulatory agency before implementation, and a rigorous verification of completion performed by means of the performance of surveys and sampling.

The logic flow is illustrated in the application of the graded approach to safety assessment for decommissioning.

Appendix V

EXAMPLE OF USE OF A GRADED APPROACH FOR GROUPING AND SPECIFYING REQUIREMENTS FOR RESIDUAL CONTAMINATION LEVELS



[a] 10 CFR 20, Appendix C

FIG. 7. Example of use of a graded approach for grouping and specifying requirements for residual contamination levels (from Ref. [85]).

TABLE 8. DESCRIPTION OF GROUPS AND ACTIONS *(from Ref. [85])*

Group	Description of group	National Environmental Policy Act action
1	Licensed material used in a manner that would preclude releases to the environment; no decommissioning plan required (limited to sealed sources and small quantities of short half-life material)	An environmental assessment for termination of the licence is not required, since this action is categorically excluded under 10 CFR 51.22(c)20 [90]
2	Would not typically be expected to result in unmonitored releases into the environment; dose screening methodology or final status survey report required	An environmental assessment is required; consider relying on the licence termination rule of the generic environmental impact statement, as described in section 15.7.3 of Ref. [85]
3	Dose screening methodology decommissioning plan required	Same as group 2
4	Typically results or has resulted in releases into the environment; volumetric contamination without existing groundwater contamination, and surface and soil contamination that does not meet screening criteria; licensee plans unrestricted use	
5	Licensed material used in a manner that resulted in releases into the environment, including groundwater contamination; licensee plans unrestricted use	An environmental assessment will be required; if groundwater is contaminated and a finding of no significant impact cannot be determined, an environmental impact statement will be necessary
6	Licensed material used in a manner that resulted in releases into the environment; licensee plans restricted use	As the licensee plans to limit future land uses at the site, the staff need to prepare an environmental impact statement; NUREG-1748 [91] discusses the process of preparing an environmental impact statement, environmental information that has to be considered by licensees in their environmental report, and the content of the environmental impact statement
7	Licensed material used in a manner that resulted in releases into the environment; licensee plans restricted use and requests use of the alternated criteria in 10 CFR 20.1404 [92]	Same as group 6

Appendix VI

WORK BREAKDOWN STRUCTURE AND WORK PACKAGES FOR DECOMMISSIONING THE NUCLEAR RESEARCH REACTOR VVR-S MAGURELE-BUCHAREST

VI.1. INTRODUCTION

The research reactor type VVR-S (tank type, water cooled, moderator and reflector, thermal power 2 MW, thermal energy 9.52 GWd) was put into service in July 1957, and in December 1997, was shut down. In 2002, the Romanian Government decided to put the research reactor into a permanent shutdown condition in order to start decommissioning. This nuclear facility had been used in nuclear research and radioisotope production for 40 years without any events, incidents or accidents. At the same site, in the immediate vicinity of the research reactor, there are many other nuclear facilities: a radioactive waste treatment plant, a tandem Van de Graaff heavy ion accelerator, a cyclotron, an industrial irradiator and a radioisotope production centre.

The main phases of the decommissioning project are:

(a) Returning the entire amount of spent nuclear fuel to the Russian Federation (2008–2010);
(b) Upgrading the radioactive waste treatment plant and national radioactive waste repository (2008–2011);
(c) Preparatory activities for the decontamination and dismantling of SSCs of the research reactor (documentation, bidding, purchasing, licensing, environmental monitoring and control on-site and off-site, training, etc.) (2008–2011);
(d) Decontamination and dismantling of SSCs (2012–2017);
(e) Final survey and release of the nuclear facilities and associated land from regulatory control (2017–2019);
(f) Redevelopment and reutilization of site for new applications in radiation technology, radiation processing and materials science (2020–2080).

The WBS of the decommissioning project consists of:

(a) Dismantling primary circuit up to reactor block (non-activated parts).
(b) Dismantling core/absorber rods, drive assembly, core components, other internal components, thermal column, cooling pond.
(c) Demolition of de-aerator, hot cells, biological shield of reactor block.
(d) Dismantling underground structures: secondary circuit, buffer tank for liquid radioactive effluents (30 m^3), connecting pipes between buffer tank and radioactive waste treatment plant.
(e) Dismantling technological ventilation, active drainage, electrical supplies for equipment used in decommissioning, air services.
(f) Dismantling auxiliary buildings (temporary structures for material storage).
(g) Final radiological survey for building and site.

VI.2. WORK PACKAGES

WP.1. Pre-decommissioning activities

1.1. Spent nuclear fuel management — removal from site;
1.2. Upgrading radioactive waste treatment plant and national repository for radioactive waste;
1.3. Commission the radiological characterization laboratory and implement the free release of materials — initial planning, packaging, storing, conditional and unconditional release from regulatory control;
1.4. Procure dosimeter system on-site;
1.5. Procure equipment for environmental protection and monitoring systems on-/off-site;
1.6. Commission mechanical workshop for cutting and light decontamination in reactor hall;
1.7. Arrange funding mechanism;
1.8. Elaboration of documentation — organizational, quality management, health and safety, security and safeguards, technical packages, transport specifications and radiation protection;
1.9. Worker route on-site;
1.10. Material route on-/off-site;
1.11. Removal from site of equipment and materials resulting from research activities and radioisotope production;
1.12. Drainage of water from primary and secondary circuit and cooling pond;
1.13. Authorization from regulatory bodies — nuclear, environmental, industrial;

1.14. Maintenance of SSCs in the transition period and during decommissioning;
1.15. Training of workers, public relations' plan, definition of stakeholders.

WP.2. Dismantling activities

2.1. Remove control/absorber rods, drive assembly, instrument and control system;
2.2. Remove primary heat exchangers and piping, pumps, water purification system;
2.3. Remove core components and internal vessels from reactor block;
2.4. Remove control room equipment;
2.5. Remove secondary circuit, buffer tank, pipes from active drainage, including underground part;
2.6. Remove cooling pond;
2.7. Remove active drainage;
2.8. Remove ventilation system.

WP.3. Decontamination activities

3.1. Decontamination of primary circuit (by washing with water and filtering in close circuit);
3.2. Decontamination of liner from hot cells with dry methods;
3.3. Decontamination of walls, floors;
3.4. Decontamination of tools and equipment used in decommissioning;
3.5. Other large pieces will be transported to the radioactive waste treatment plant for decontamination in a special room.

WP.4. Demolition activities

Demolition of biological shields from reactor block, hot cells, de-aerator and stack.

WP.5. Radiological characterization, packaging

Transport, disposal, storage, free release, final survey, archiving.

Conclusion: Decommissioning of a nuclear research reactor is a complex project.

The nuclear regulatory body requires the elaboration and approval of a quality control manual prior to the start of the project. The use of WPs creates the possibility to elaborate and approve the procedure applied for activities grouped at the same location; work instructions have been elaborated for the specific equipment used.

Appendix VII

EXAMPLE OF END STATES OF DECOMMISSIONING PHASES FROM THE DECOMMISSIONING OF THE MULTIPURPOSE RESEARCH REACTOR MZFR, KARLSRUHE, GERMANY

The multipurpose reactor MZFR [93] was a pressurized water reactor, cooled and moderated with heavy water. It was built from 1961 to 1966, and went critical for the first time on 29 September 1965. After 19 years of successful operation, the reactor was shut down on 3 May 1984. The reactor had a thermal output of 200 MW, and an electrical output of 50 MW.

In addition to generating electricity, the MZFR had the following functions:

- Testing fuel assemblies and various materials for reactor construction;
- Gaining experience in the design, erection and operation of heavy water reactor systems;
- Training scientific and technical reactor personnel;
- Providing heat (first nuclear combined heat and power system (1979–1984)).

In 1989, it was decided to dismantle the reactor completely, step by step. The decommissioning concept for the plant, down to a greenfield site, provides for eight distinct decommissioning steps (phases). A separate decommissioning licence was required for each step. The decommissioning work was carried out according to pre-approved work schedules.

About 72 000 t of concrete and 7200 t of metal were to be removed. About 1000 t of concrete (500 t biological shield) and 1680 t of metal were to be classified as radioactive waste.

VII.1. PHASES

The first measures taken (1984–1987) were the removal of the fuel assemblies and the heavy water from the plant. Within the first and second phases, systems no longer needed were de-activated, while the systems still needed were modified; the heavy water systems were drained and dried in preparation for dismantling.

During the third decommissioning phase, the cooling towers were demolished, the turbine hall was cleared and the water conditioning facilities were dismantled. The cleared turbine hall was provided to a working group from the Karlsruhe Reprocessing Plant for erecting and operating a test bed for remote controlled disassembly of equipment in the Karlsruhe Reprocessing Plant.

During the fourth decommissioning phase, the dismantling of reactor auxiliary systems in the auxiliary system buildings and in the fuel assembly storage building was carried out, and the electricity supply system was simplified. The primary system was decontaminated chemically in preparation for dismantling. The mean decontamination factor was 15, reducing the dose rate such that manual dismantling became possible.

The fifth decommissioning phase covered the removal of safeguard facilities in the area of the MZFR, and the removal of the fence and surveillance equipment surrounding the area of the MZFR.

The sixth decommissioning phase mainly involved the dismantling of the primary systems and all reactor auxiliaries in the reactor building, as well as the decontamination of cleared auxiliary system buildings for release. After completion of the work, the reactor building was empty, except for the reactor pressure vessel and its internal components.

The seventh decommissioning phase covered the dismantling of the reactor pressure vessel and its internal components manually and by remote control, followed by the clearing of the reactor building.

The eighth and last decommissioning phase includes the removal of the activated concrete in the biological shield, the dismantling of the remaining systems, the decontamination of the building structures, the demolition of the concrete structures (reactor building, outdoor facilities), the processing of the tritium-contaminated concrete rubble from the demolition, and the clearing and recovery of the site.

Appendix VIII

GENERIC CHECKLIST FOR HAZARD IDENTIFICATION

Hazards	Relevant for planned work	Relevant for accidents
	Yes/no	**Yes/no**
Radiological hazards		
Direct radiation sources		
Improper removal of shielding		
Radioactive material, including form (solid, liquid, gaseous)		
Criticality		
Contaminated liquid, material		
Other radioactive sources (smoke detectors, lightning rods)		
Fire/explosion hazards		
Oxygen		
Sodium		
Explosive substances		
Flammable gases (e.g. oxyacetylene, propane gas), liquids, dust		
Combustible/inflammable materials		
Compressed gases		
Hydrogen generation		
Overheating or fire, caused by, for example, portable heaters, overload of electrical circuits, application of cutting techniques		
Electrical hazards		
High voltages		
Power overload and shortcuts, power failures		
Inadequately disconnected circuits/prevention against inadvertent connection		

Hazards	**Relevant for planned work**	**Relevant for accidents**
Non-ionizing radiation hazards		
Non-ionizing radiation sources, including lasers		
Electromagnetic radiation (e.g. microwaves)		
High intensity magnetic fields		
Chemical/toxic hazards		
Chemotoxic material		
Spills		
Chemicals (aggressive chemicals)		
Accidental mixing/combination of chemicals (e.g. in sewage systems, decontamination work)		
Asbestos and other hazardous materials, such as lead or beryllium		
Pesticide use		
Biohazards		
Physical hazards		
Kinetic energy		
Potential energy (springs, Wigner energy in graphite)		
Degraded or degrading structures, systems and components		
Steam		
Temperature extremes (high temperatures, hot surfaces, cryogenics)		
High pressure (pressurized systems, compressed air)		
Working environment hazards		
Working at heights (e.g. ladders, scaffolding, man baskets)		
Excavations, formation of underground cavities (subsidence) from rain, waste degradation, etc.		

Hazards	Relevant for planned work	Relevant for accidents
Vehicle traffic		
Heavy lifts, material handling, heavy equipment, manual lifting, overhead hazards, falling objects, cranes		
Inadequate illumination		
Inadequate ventilation		
Noise (high noise areas and tools)		
Dust		
Pinch points, sharp objects		
Confined space		
Dangerous equipment, e.g. power tools, compressed gas cylinders, welding and cutting, water jet cutting/decontamination, abrasive decontamination techniques, grinding, sawing		
Remote work area		
Obstruction of passageways or exits		
Human/organizational hazards		
Human error		
Safety culture aspects		
Assigning inadequate training for work steps		
Assigning inadequate protective measures for work steps		
External hazards/initiating events		
Ambient temperature extremes		
Aeroplane crash		
Storm and adverse weather conditions		
Earthquakes		
Flooding		
External explosions and fires		

Hazards	Relevant for planned work	Relevant for accidents
Other hazards		
Degraded/corroded barriers, ageing of materials		
Unknown or unmarked materials		
Spills		

Appendix IX

EXAMPLE LIST OF HAZARDS AND RISKS ASSOCIATED WITH TYPICAL DECOMMISSIONING ACTIVITIES

TABLE 9. PLANNED ACTIVITIES

Hazard	Risk/pathway	Control
Decontamination, wet/dry		
Used radioactive decontamination solution and free radioactive liquids	External radiation to workers; Routine atmospheric and liquid releases; Internal contamination of workers	Organization of work, use of shielding; Stack and effluent monitoring; Adequate masks and protective clothing
Collected contaminated dust particles on dust extractor filters	External radiation to workers; Internal contamination of workers	Organization of work, use of shielding; Adequate masks and protective clothing
Airborne aerosols released from liquids, foams, dust at work-place	Internal exposure to workers from inhalation; Atmospheric routine release	Use of protective masks; Stack monitoring with annual limits
Decontamination solutions, foams	Chemical toxicity to lungs and skin of workers	Protection of breath (masks) and skin (protective gloves and clothing)
Dismantling, cutting and manipulation with large pieces/equipment and parts		
Radioactive parts of dismantled equipment	External radiation to workers	Organization of work, use of shielding
Dismantling of parts with traces of residual oils inside	Fire	Adequate drainage and availability of local fire extinguishers
Airborne aerosols and gases released at work-place	Internal exposure to workers from inhalation; Atmospheric routine release	Respiratory protection, masks; Stack monitoring with annual limits
Collected activated or contaminated dust particles on dust extractor filters	External radiation to workers; Internal contamination of workers	Organization of work, use of shielding; Adequate masks and protective clothing

TABLE 9. PLANNED ACTIVITIES (cont.)

Hazard	Risk/pathway	Control
Low contaminated materials, decontaminated and dismantled	External radiation and internal contamination to workers; Exposure to the public through free release	Organization of work, use of shielding; Free release measurements
Physical injury to workers	Fall from ladders or scaffolding; Being hit by falling objects; Injuring the head during work in narrow compartments; Injuries to hands; Tripping over objects on the floor	Use of certified equipment and adherence to occupational health regulations; Use of helmet and safety shoes; Use of gloves; Keep tidy
Electric shock to workers	Cutting or dismantling cabling that has not been disconnected	Securing the disconnection of the electricity supply to the system to be dismantled
Radioactive waste handling		
Treatment of liquid, dust and solid radioactive waste	Exposure and contamination to workers and the environment via complex pathways	Organization of work, use of shielding, masks and protective clothing; Stack and dumping monitoring
New solidified radioactive waste, transport and manipulation	External radiation to workers	Organization of work, use of shielding

TABLE 10. INCIDENTS AND ACCIDENTS

Hazard	Risk/pathway	Control
Decontamination, wet/dry		
Spill of decontamination fluid	External and internal exposure to workers performing mitigating actions	Organization of work, use of shielding and adequate clothing and masks for protection of workers from chemical hazards
Fire, spread of steam and aerosols from radioactive materials, solutions and chemicals	Accidental airborne radioactive and chemical release; Inhalation of radioactive and toxic substances to workers; External radiation to workers	Active ventilation; Use of adequate masks for protection of workers from radioactive and chemical hazards
Failure of ventilation system	Inhalation of radioactive substances to workers	Monitoring of ventilation performance; Use of adequate masks
Flood of radioactive solutions	Liquid release to surface water and underground water; External and internal exposure to workers performing mitigating actions	Flood control measures; Test of groundwater contamination; Monitoring of radiation
Fall of radioactive piece or equipment	External radiation to workers	Monitoring of radiation; Protective clothing; Use of shielding
Leak of liquid radioactive waste reservoir	Release to underground water and the environment; External and internal exposure to workers	(Periodic) integrity and material controls; Groundwater test for radioactive contamination; Use of shielding and adequate clothing and masks

Appendix X

EXAMPLE OF SPECIFIC HAZARDS ANALYSIS RECORD

TABLE 11. EXAMPLE OF DOCUMENTATION OF INITIATING EVENTS, CONTROLS AND ASSESSMENT RESULTS

Hazard/energy source	Description	Location	Preventive/mitigative control available	Evaluation
1. High voltages				
List the specific equipment, material or activity that represents the condition	*List the specific material/equipment or action that is under consideration*	*Identify the specific room where such equipment is located*	*Identify systems or programmes that may be available to prevent an event or reduce its consequences*	*Identify consequences of failure or potential events*
A.A. 13.8 kV distribution system	Building transformers step down 13.8 kV to 480 V power; 13.4 kV service will be isolated and equipment dismantled and removed; Cranes may work in areas with high voltage lines overhead		Uninterruptible power supply, diesel generator, ground fault protection Lockout/tagout, system, maintenance; Occupational safety and industrial hygiene — electrical safety	Shock; Electrocution; Death; No direct release from facility Potential scenarios: Loss of power; Fire

TABLE 12. EXAMPLE OF DOCUMENTATION OF HAZARD EVALUATION FORMS

Identifier	Type	Cause	Material	Unmitigated		Potential controls		Mitigated	
				Frequency	Receptor/dose	Prevention	Mitigation	Frequency	Receptor/risk
Identifies the scenario that will be modelled	*List the type of event or accident*	*Those hazards that could result in an event*	*List the material from inventory typically bounding*	*Estimated frequency of occurrence without control*	*Identify the receptors of concern and the estimated resulting dose (may be qualitative)*	*List reasonable controls that can preclude an event*	*List reasonable controls that may reduce the consequences of an event*	*Estimated frequency of occurrence with control*	*Identify receptors of concern and the estimated resulting dose (may be qualitative)*
E-1	Fire[a]	Electrical, thermal, friction, pyrophoric material, open flame, flammables, combustibles, chemical reaction	5.975 g Pu-239	Anticipated	Immediate worker — high; Co-located worker — moderate; Member of a critical group — low	Combustible loading control, hot work permit, flammable gas and liquid restriction, fire retardant materials	High efficiency particulate air filtration, fire detection, suppression, alarm	Anticipated	Immediate worker — moderate; Co-located worker — low; Member of a critical group — low
E-2	Explosion	Explosive material, chemical reactions, potential (pressure)							
E-3	Loss of containment or confinement	Kinetic — linear and rotational (friction); Potential (height, mass)							

TABLE 12. EXAMPLE OF DOCUMENTATION OF HAZARD EVALUATION FORMS (cont.)

Identifier	Type	Cause	Material	Unmitigated		Potential controls		Mitigated	
				Frequency	Receptor/dose	Prevention	Mitigation	Frequency	Receptor/risk
E-4	Direct radiological exposure	Ionizing radiation							
E-5	Nuclear criticality	Fissile material							
E-6	External hazards	Cranes, non-facility events, vehicles in motion							
E-7[b]	Natural phenomena								

[a] Additional cases may be presented evaluating different degrees of severity of the event. The safety analysis would typically also include small and moderate fires.

[b] The analysis needs to include consideration of natural phenomena hazards for the decommissioning case only in the event that the facility will have an extended life (e.g. more than 5 years), or the decommissioning activities will require modification that would affect the evaluation performed for the operating case (e.g. the structural capacity reduced before corresponding material is removed). The facility structure and systems that provide protection in the event of a natural phenomenon hazard event should be preserved until it becomes impractical to support the systems, the risk has been substantially reduced and the consequences of failure in such an event would not be unacceptable. The facility will be required to meet basic building codes to protect life during work activities that require habitation of the facility. Detailed dynamic analyses and stress evaluations are not required in any case.

Appendix XI

ACCIDENT CONSEQUENCES AND RISK CLASSIFICATION

Table 13 provides a basis for classifying accident scenarios based on risk. A preliminary safety assessment is used to assess unmitigated radiological consequences and a frequency band determined on a conservative basis. From the table, the appropriate risk class can be determined for each scenario. Facility classification can be allocated on the basis of the highest risk class determined.

When accident scenarios become complicated (because multiple outcomes are possible), it may be necessary to use event trees or fault trees to adequately track and describe frequencies and illustrate dominant scenarios, though the need for this will be rare in decommissioning safety assessment. The frequency of the event should be taken into consideration, not merely a single element of the fault tree. For example, although the frequency of a vehicle accident may be anticipated, an accident that strikes and breaches material containers, and catastrophically ruptures the fuel tank and ignites would not be considered anticipated.

The definitions and requirements in the safety assessment for each of the four risk classes are as follows:

(a) Risk class I events are essentially those that could have a significant off-site consequence; therefore, the public must be protected with higher integrity engineered safety measures (SSCs) and administrative safety measures (with engineered measures being preferred). Events resulting in high off-site radiological consequences must be subject to detailed safety assessment, irrespective of the assessed frequency of occurrence.

(b) Risk class II events are those that have lesser off-site consequences than risk class I, but significant on-site effects. Both classes I and II must also be considered for protection with high level SSCs and administrative safety measures. The consideration of control(s) should be based on the effectiveness and feasibility of the considered measures. Further controls for class I and II accident sequences should be considered over and above the requirements of the accident safety criteria, if it is justified on ALARA grounds. This is sometimes described as defence in depth.

(c) Risk class III events are those with localized consequences. They are generally considered to be adequately protected by the operator’s safety management programme. Class III accidents may be considered for defence in depth safety measures, if justified on ALARA grounds. A formal

TABLE 13. ACCIDENT CONSEQUENCE VERSUS FREQUENCY — RISK CLASSIFICATION SYSTEM

Consequence level	Beyond extremely unlikely	Extremely unlikely	Unlikely	Anticipated
	($<10^{-6}$/a)	(10^{-4}–10^{-6}/a)	(10^{-2}–10^{-4}/a)	(10^{-1}–10^{-2}/a)
High consequence Off-site public (>100–1000 mSv) On-site (>1000 mSv)	III	II SAR, safety significant controls	I SAR, safety class controls for the public, safety significant for workers	I SAR, safety class controls for the public
Moderate consequence Off-site public (>10–100 mSv) On-site (>100–1000 mSv)	IV	III	II SAR	I SAR
Low consequence[a] Off-site public (<1–10 mSv) On-site (>10–100 mSv)	IV	IV	III	III

[a] SAR: safety assessment report.

safety assessment would not normally be required, unless required by the regulatory body.

(d) Risk class IV events are those with low consequences and do not require additional safety measures, but are considered to be adequately protected by the operator’s safety management programme, and consequently a documented safety assessment is not usually required.

It is common practice to classify a facility based on the highest risk class arising from the unmitigated accident safety assessment. This classification can then be used to define the level of independent review and the regulator’s review of the safety assessment. For example, a risk class I facility safety assessment would be subject to full internal independent review, as well as regulatory review. A risk class II facility may only be subject to internal review, unless the regulator specifically chooses to carry out a review.

Appendix XII

EXAMPLE OF PATHWAYS FOR GENERIC SCENARIOS

Building an occupancy scenario

This scenario accounts for exposure to be fixed and removable residual radioactive material on the walls, floor and ceiling of a decommissioned facility. It assumes that the building may be used for commercial or light industrial activities (e.g. office building or warehouse).

Pathways include:

— External exposure from building surfaces;
— Inhalation of (re)suspended removable residual radioactive material;
— Inadvertent ingestion of removable residual radioactive material.

A resident farmer scenario

This scenario accounts for exposure involving residual radioactive material that is initially in the subsurface soil. A farmer moves on to the site and grows some of his/her diet, and uses water tapped from the aquifer under the site.

Pathways include:

— External exposure from soil;
— Ingestion of soil;
— Ingestion of drinking water from the aquifer;
— Ingestion of plant products grown in contaminated soil and use of the aquifer to supply irrigation needs;
— Ingestion of animal products grown on-site (using feed and water derived from potentially contaminated sources);
— Ingestion of fish from a pond filled with water from the aquifer.

Appendix XIII

EXAMPLE OF FACILITY/DECOMMISSIONING CLASSIFICATION

Risk class	Fundamental definition	Interpretation
I	Off-site hazard	≥5 mSv public off-site
II	On-site hazard	≥5 mSv on-site or ≥20 mSv in a building
III	Hazard in a building	≥0.02 mSv public off-site or ≥0.5 mSv on-site or ≥5 mSv in a building
IV	Hazard confined to local work area	<0.02 mSv public off-site or <0.5 mSv on-site or <5 mSv in a building

Appendix XIV

EVALUATION MODEL FOR COLLECTIVE OCCUPATIONAL DOSE IN DECOMMISSIONING

Collective occupational doses by external exposure can be estimated by considering the characteristics of dismantling activities in nuclear reactor facilities. Evaluation models were developed for the estimation of collective occupational doses by external exposure in planning of dismantling activities [94–98].

XIV.1. CHARACTERIZATION OF WORK ACTIVITIES IN ACTUAL DISMANTLING WORK

In order to estimate collective occupational doses, dismantling activities for nuclear power plants were characterized in terms of estimated radiation dose rates and labour hours, since external exposures can be basically calculated by multiplying dose rate by labour hours at a work area.

In general, occupational doses strongly depend on work activities and on the components and structures to be dismantled because they have various levels of radioactive contamination. Actual occupational doses were ten times larger in dismantling than those in the post-dismantling cleaning of the reactor pressure vessel of the Japan Power Demonstration Reactor because radioactive sources had already been removed from the area in this phase. Radiation dose rates in the area are very different before and after removal of radioactive components and structures.

Furthermore, the actual number of dismantling labour hours was less than the total daily work activities; that is, workers were not always near the components and structures all day long. Daily work activity items consisted of dismantling, entering and exiting controlled areas, transporting containers and cleanup of work areas. It was found that the dismantling time was from 1 to 2 h per worker in a day, and it took approximately 2 h for entering and exiting the controlled area, preparatory work and cleaning up.

A work crew consisted of four or five workers, a supervisor, a health physics technician and a technical consultant for dismantling. The workers carried out cutting activities on components and structures, and were exposed to relatively higher radiation levels. For instance, a worker's average individual dose was approximately eight times higher than a technical consultant's dose.

XIV.2. WORK BREAKDOWN STRUCTURE

It is important for estimating external occupational doses to break down dismantling activities into categories. WBSs are usually employed to facilitate and understand the project work activity scope. Therefore, the WBS method was applied to estimate external occupational doses. Each dismantling activity, such as the dismantling of reactor internals and the removal of bioshield concrete, is divided into categories of preparatory activity, dismantling and packaging, and post-dismantling cleanup.

XIV.3. CATEGORIZATION OF DAILY WORK, LOCAL AREA AND CREW ARRANGEMENT

For modelling of occupational dose estimation, occupational types, dose rate distribution in a work area, crew arrangement and daily work activity items were taken into consideration.

Daily work activities are divided into three divisions: (i) entering and exiting of controlled areas, (ii) pre- and post-activities for preparation and cleanup, and (iii) main activities at a local area with a higher dose rate.

XIV.4. DEVELOPMENT OF AN EVALUATION MODEL FOR COLLECTIVE OCCUPATIONAL DOSE

In general, an individual external dose is calculated by multiplying the dose rate by labour hours in the area. Collective occupational doses by external exposure are basically obtained by integrating the individual doses throughout the whole period. On the basis of the dismantling characteristics described above, a calculation model of collective occupational doses (D) is designed as follows:

$$D = \sum_i \sum_j \sum_k R_{ijk}(t) \cdot N_{ij} \cdot r_{ik} \tag{1}$$

where

D is the collective occupational dose (person mSv);
$R_{ijk}(t)$ is the average dose rate in the local area for each category, occupational type and daily work activity (mSv/h);
N_{ij} is the manpower for each occupational type and category (h);

r_{ik} is the working time ratio for each occupational type and daily work activity;

i is the occupational type of workers;

j is the category of each dismantling activity (preparatory activity, dismantling and post-dismantling cleaning up);

and k is the daily work activity.

As indicated in the calculation model of Eq. (1), $R_{ijk}(t)$ is one of the major parameters for estimating collective occupational doses. A calculation code for dose rate such as QAD-CGGP2 was applied to obtain dose rate distribution maps. It enables the calculation of mesh wise dose rates on a selected plane in the work area based on the input of radioactive sources and geometrical configurations. The dose rate in a local area is calculated by averaging values at mesh points of the estimated moving areas of workers.

N_{ij} is also one of the major parameters used to estimate collective occupational doses. The manpower for each occupational type and category is calculated by a project management code such as COSMARD, which includes the WBS methodology. A structure was designed to put working time ratios as a parameter for setting daily work activity in terms of r_{ik}.

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INTERNATIONAL ATOMIC ENERGY AGENCY
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ISBN 978–92–0–141410–6
ISSN 1020–6450