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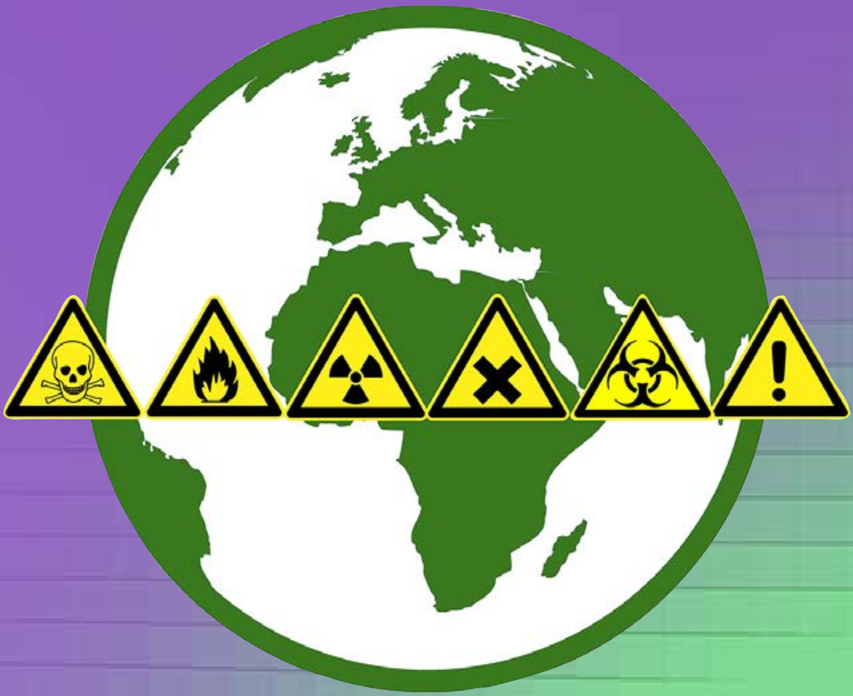
Risk and safety assessments supporting regulatory supervision of decommissioning and waste management for nuclear research and radiation facilities

Report of a joint Nordic workshop, 9–11 February 2021



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Emneord

Atomforskning, sikkerhetsvurderinger, avvikling, avfallshåndtering, regulatorisk tilsyn

Resymé

Rapporten gir en omfattende oversikt fra en Nordisk workshop om «Risiko- og sikkerhets-vurderinger som støtter regulatorisk tilsyn med avvikling og avfallshåndtering for kjernefysisk forskning og atomanlegg». Workshopen ble organisert av DSA og Center for Environmental Radioactivity (CERAD). Vesentlig praktisk informasjon deles og diskuteres, og en rekke konklusjoner og anbefalinger trekkes for fremtidig vurdering, inkludert utvikling av relevant forskning.

Reference

Sneve M.K. Risk and safety assessments supporting regulatory supervision of decommissioning and waste management for nuclear research and radiation facilities. Report of a joint Nordic workshop, 9 – 11 February 2021. DSA Report 2021:3. Østerås: Norwegian Radiation and Nuclear Safety Authority, 2021. Language: English.

Key words

Nuclear research, safety assessments, decommissioning, waste management, regulatory supervision

Abstract

This report provides a comprehensive record of a joint Nordic workshop on 'Risk and safety assessments supporting regulatory supervision of decommissioning and waste management for nuclear research and radiation facilities". The workshop was organized by the DSA and the Centre for Environmental Radioactivity (CERAD). Substantial practical information is shared and discussed, and a range of conclusions and recommendations drawn for future consideration, including the development of relevant research activities.

Godkjent:

Per Strand

Per Strand, direktør

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DSA,
postboks 329, 0213
Oslo
Norge.

Telephone 67 16 25 00
Fax 67 14 74 07
E-mail dsa@dsa.no
dsa.no

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Risk and safety assessments supporting regulatory supervision of decommissioning and waste management for nuclear research and radiation facilities.

Report of a joint Nordic workshop, 9 – 11 February 2021.

Preface

The following welcoming words set the scene for this report of a workshop hosted by the DSA and Centre for Environmental Radioactivity (CERAD), 9 – 11 February 2021, on the subject of Risk and Safety Assessments Supporting Regulatory Supervision of Decommissioning and Waste Management for Nuclear Research and Radiation Facilities.

> "Dear colleagues,
>
> Welcome to the Nordic workshop on Risk and Safety Assessments Supporting Regulatory Supervision of Decommissioning and Waste Management for Nuclear Research and Radiation Facilities organized by DSA and CERAD.
>
> There has been long-standing cooperation between Norway, Denmark, Sweden and Finland in research activities and projects related to the development and application of nuclear and ionizing radiation technologies. Here in Norway, we have recently accelerated the decommissioning programme arising from earlier than expected closure of the JEEP II and Halden research reactors. Other Nordic countries have similar challenges. For example, in Finland, there is the Otaniemi research reactor currently under decommissioning, with a number of options for waste management still open; the Riso research reactor in Denmark, and the Studsvik R2 and R2-0 reactors in Sweden. Other facilities of possible interest include experimental fuel facilities and stores, cyclotrons and irradiation facilities. The decommissioning challenges are typically complex since many of the facilities are old and were designed before the development and use of modern design requirements.
>
> DSA recognizes the role of assessments in supporting regulatory decisions affecting decommissioning and waste management. based on reliable information underpinned by good science, on topics such as:
>
> - waste and site characterization,
> - measurements and assessments that support regulatory approval of decontamination and dismantling activities,
> - atmospheric and liquid radioactive discharges to the environment during decommissioning operations,
> - and treatment, interim storage and final disposal of solid radioactive waste.
>
> At the same time, it is important to develop and apply a broad view of optimization, accounting for complex issues of risk communication and engagement with the full range of stakeholders potentially affected by management decisions.
>
> I hope the discussions will be valuable first of all for DSA and CERAD, but also for our Nordic colleagues and the wider international community. We will not solve all the challenges at one meeting, but I hope this is the start of a longer-term dialogue".
>
> **Per Strand,** Director General, Radiation and Nuclear Safety Authority, Norway

Presentations given at the workshop, conclusions and recommendations are summarized in the current report. The DSA is very grateful for the support of workshop participants, and for their review of the draft of this report, and to CERAD for support in the organization of the workshop.

The opinions and other material presented in the report may not be taken to represent the views of the organizations involved.

Executive Summary

There has been long-standing cooperation between Norway, Denmark, Sweden and Finland in research activities and projects related to the development and application of nuclear and ionising radiation technologies. Many of the facilities linked to these projects have either already commenced decommissioning or are due to in the near future. Alongside power reactors and other major facilities within the nuclear fuel cycle, they include research reactors and other facilities and sites that generate, manage or use radioactive materials, such as experimental fuel examination facilities, cyclotrons and irradiation facilities. The decommissioning of these nuclear research and radiation facilities and sites, and management of related radioactive wastes, is typically complex since many of them are old and were designed and constructed before the development and implementation of modern design requirements. Many were operated for years prior to the promulgation of modern safety standards, and some were 'closed' or 'decommissioned' according to the standards of the time but now need more complete decommissioning. A key feature of many research facilities is that they have undergone modification over time as the focus of research has evolved. This is distinct from a power reactor that generally has only a single purpose and a well-defined upgrade path. Thus, research facilities may be smaller, but they are more complex as well as unique. Special guidance is therefore required to support the efficient and effective regulatory supervision and management in the circumstances that prevail.

The workshop described in this report focused on risk and safety assessments supporting regulatory supervision of these activities, and related research needs. It provided an opportunity to bring together regulators and operators, to share experience of practical challenges faced and different perspectives on what is important and what is still needed in terms of making and reviewing safety cases, and how the science community can help in addressing those challenges.

Participation included 54 representatives from Nordic regulators, operators, scientific and technical support organizations and other stakeholders, and experts within the fields of risk assessment and radioecology. It was organized as a webinar over three days covering the following topical areas:

1. **Experience**: Encompassing lessons learned from legacy sites, decommissioning and waste management experience; experience in the selection of reference levels, constraints and other criteria for control of risks to people and the environment; and implementation of holistic/multi-risk/graded approaches.
2. **Methodology**: Radiological and other risk assessment methods that support proportionate and optimized management of different hazards and risks to workers, members of the public and the environment and identification of key scientific uncertainties that affect safety assessment based on practical examples.
3. **Challenges**: Dissemination and sharing information on past and ongoing research conducted to reduce scientific uncertainties, including methods and results for improved waste characterization, site characterization, identification of continuing challenges and the scope for them to be addressed through research, and sharing of experience on risk communication.

As well as presentations on the above topics, group discussions were held, aimed at eliciting input and views on the following questions:

- → What are the key contaminants (both radioactive and non-radioactive) from research facility decommissioning and what makes them key?
- → What environmental media / exposure pathways are important for these key contaminants?
- → What site characterization data are important?
- → Are the answers different for current operations and for releases into the future?

The working group discussions were very productive in building on the presentations made. The mix of experience within groups and the different disciplines represented allowed discussion around cross-cutting issues. Such an approach is considered very beneficial since, when addressing decommissioning, legacy and waste management issues, experience has shown that a multi-disciplinary approach is needed to address the diverse hazards and issues that may be present.

The following challenges, research needs and recommendations were identified:

- Key contaminants from research reactors and related facilities can differ from those typically associated with commercial reactors and information on their characteristics is often lacking. Even for the more common contaminants, knowledge on their behavior can be lacking for ecosystems that are quite specific to Scandinavian scenarios. As such, there would be merit in identifying key contaminants (both radioactive and chemical) for which information on environmental behavior is lacking for key Nordic environments. Research targets could then be developed and undertaken to provide necessary knowledge and data in support of safety assessments.
- Research reactors present their individual challenges, with each being different. Nonetheless, there is the opportunity to learn from the experience of others in developing safety cases from an operator’s perspective and in their review from the perspective of regulators. It could be useful, therefore, to review past experience and consider lessons learned in terms of what worked well, what were the key challenges faced, what prevented decisions from being made and how that knowledge and experience can be used to support decommissioning and related waste management programmes.
- There is also the opportunity to look further into lessons learned from previous site characterization strategies, including effective stakeholder engagement. Characterization is a vital part of any decommissioning, legacy or waste management programme and considerable experience has already been gained. It could be useful to gather together experience and review lessons learned around what to characterize and how and when sufficient characterization has been achieved.
- Stakeholder engagement continues to be an issue for many programmes. Again, opportunities arise to benefit from drawing together experience of how stakeholder dialogue has been approached and implemented in different programmes, what did or did not work well, what issues were faced and the causes of those issues. Focus could be given to key technical areas and how the main messages are better communicated with different stakeholders. Communication about risk can be a particular challenge and it may be possible to develop a framework for effective stakeholder engagement that is based on real-world experience and lessons learned.
- There is a tendency in research programmes to focus on single issues or topics. There may be merit, however, in taking a more cross-cutting approach whereby several issues are considered together in order to find the optimum way forward that takes account of the range of issues faced. As an example, a research project could look at how to carry out effective dialogue between relevant stakeholders that addresses different hazards and risks.
- The use of a harmonized and proportionate approach to decommissioning, legacy and waste management is commonly and positively referred to. However, developing and applying such an approach is challenging. Decommissioning and legacy sites are often associated with a wide range of radiological, chemical and physical hazards and complex social contexts. Different regulations may apply and there may be different regulatory bodies overseeing the management of different hazards, which adds to the challenge. Nonetheless, there would be merit in drawing together experience of approaches that have been adopted or adapted to address these issues This would also support the identification of research that would support the development and application of harmonized and proportionate assessments of risk from different hazards. There is also an opportunity to consider harmonization of approaches between countries through the

development of a common framework. The optimum solution may be locally specific, but the method to identify and implement it can include common features. In addition, adoption of a common approach is likely to offer its own benefits. Such benefits need to be weighed against the advantages of local flexibility.

- Finally, continued exchange of science information across Nordic countries is considered very beneficial. This could take the form of a collaborative forum that brings together operators, regulators and the scientific community to continue to discuss the challenges faced in decommissioning, legacy and waste management programmes in different countries and to identify common research needs that can be supported through shared resources. Such an approach can help secure the necessary funds to allow academic research to progress whilst avoiding issues arising from perceptions that research is not sufficiently independent. The provision of funds for academic research on widely acknowledged, but, scientific questions could also help in developing necessary skills and competencies.

Abbreviations and acronyms

BKAB	Barsebäck Kraft AB
CatchNet	Catchment Transport and Cryo Hydrology Network
CDLM	Committee on Decommissioning and Legacy Management
CERAD	Centre for Environmental Radioactivity
D&D	Dismantling & demolition
DISC	Design for Integrated Safety Culture
DSA	Norwegian Radiation and Nuclear Safety Authority
EGLM	Expert Group on Legacy Management
EURAMET	European Association of National Metrology Institutes
GAP	Greenland Analogue Project
GRASP	Greenland Analogue Surface Project
HWBR	Heavy-water boiling water reactor
IAEA	International Atomic Energy Agency
IFE	Institute for Energy Technology
NCTP	NIVA Computational Toxicology Program
NEA	Nuclear Energy Agency
NIVA	Norwegian Institute for Water Research
NND	Norwegian Nuclear Decommissioning
NPP	Nuclear Power Plant
NWMO	Canadian Nuclear Waste Management Organization
OECD	Organization for Economic Co-operation and Development
QSAR	Quantitative structure-activity relationships
RIC	Ranstad Industricenctrum AB
SAR	Safety analysis report
SFL	Swedish low-level and intermediate long-lived nuclear waste repository
SFR	Swedish repository for short-lived radioactive waste
SKB	Swedish Nuclear Fuel and Waste Management Company
SNF	Spent nuclear fuel
SSM	Swedish Radiation Safety Authority
STOP	Source to Outcome Pathway
STUK	Finnish Radiation and Nuclear Safety Authority
US	United States
VTT	Technical Research Centre of Finland
WPN	Work package notification

Content

1 Introduction

1.1 Background

There has been long-standing cooperation between Norway, Denmark, Sweden and Finland in research activities and projects related to the development and application of nuclear and ionizing radiation technologies. Many of the facilities linked to these projects have either already commenced decommissioning or are due to in the near future. Alongside power reactors and other major facilities within the nuclear fuel cycle, they include research reactors and other facilities and sites that generate, manage or use radioactive materials, such as experimental fuel examination facilities, cyclotrons and irradiation facilities.

The decommissioning of these facilities and sites, and management of related radioactive wastes, is typically complex since many of them are old and were designed before the development and implementation of modern design requirements. They had often operated for years prior to the promulgation of modern safety standards, and some were ‘closed’ or ‘decommissioned’ according to the standards of the time but now need more complete decommissioning. A key feature of many of many research facilities is that they have undergone modification over time as the focus of research has evolved. This is distinct from a power reactor that generally has only a single purpose and a well-defined upgrade path. Thus, research facilities may be smaller, but they are more complex and may present unique features. Special consideration is therefore required to support the efficient and effective regulatory supervision and management in these circumstances.

The process of decommissioning leads to the generation of waste which will, in due course, require disposal as radioactive waste in specialized facilities or clearance as non-radioactive waste, while in both cases taking into account the non-radioactive hazardous components. Wastes include spent fuel from research reactors and experimental fuel materials linked to research projects. These are of much smaller volume than the spent fuel from power reactors but present a wide variety of characteristics which may mean that they are not conveniently managed within a wider spent fuel management programme linked to power reactors. In addition, dismantling results in a range of less active wastes, many of which have significantly different characteristics from those arising during operation. Wastes arising from old facilities and research projects also tend to not be well characterized and information about them is often very limited.

These facilities and related wastes therefore typically present features that are characterized internationally as legacies[1]. The value of international cooperation in this area has been illustrated in several international publications. Notable examples include:

- Nuclear Energy Agency of the Organization for Economic Co-operation and Development (NEA-OECD) (in press). Characterization Methodology for Unconventional and Legacy Waste. Report of the NEA-OECD Expert Group on the Characterization Methodology of Unconventional and Legacy Waste. NEA-OECD, Paris.
- NEA-OECD (2019), Challenges in Nuclear and Radiological Legacy Site Management: Towards a Common Regulatory Framework, NEA No. 4719. NEA-OECD, Paris.
- Sneve M K et al. (2020). Regulatory Framework of Decommissioning, Legacy Sites and Wastes from Recognition to Resolution: Building Optimization into the Process. Report of an international workshop, Tromsø, 29 October – 1 November 2019. DSA Report 2020:05.

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[1] https://www.oecd-nea.org/jcms/pl_25186/committee-on-decommissioning-of-nuclear-installations-and-legacy-management-cdlm

- Sneve M K et al. (2018). Regulatory Supervision of Legacy Sites: The Process from Recognition to Resolution. Report of an international workshop, Lillehammer, 21-23 November 2017. Stra˚levernRapport 2018:4.
- BIOPROTA (2015). Comparison of Safety and Environmental Impact Assessments for Disposal of Radioactive Waste and Hazardous Waste. Report of an International Workshop organized through the BIOPRPOTA Forum, published as Stra˚levernRapport report 2015:8.

Key challenges to regulatory decision-making include waste and site characterization and, in particular, measurements and assessments that support regulatory approval of decontamination and dismantling activities, atmospheric and liquid radioactive discharges to the environment, and treatment, interim storage and final disposal of solid radioactive waste. Experience suggests that optimization is a complex process that should include comprehensive consideration of radiological and other risks and benefits associated with management options, as well as engagement with the full range of stakeholders potentially affected by management decisions.

The recent setting up of the NEA Expert Group on Holistic Process for Decision Making on Decommissioning and Management of Complex Sites2 illustrates the widely recognized need for further international cooperation to address challenges in delivering holistic optimization and proportionate risk management, taking into account the complex mixture of exposure situations and risks that can occur.

Noting the above, a joint Nordic workshop was organized on risk and safety assessments supporting regulatory supervision of decommissioning and waste management, focusing on nuclear research and radiation facilities. The workshop was held as a webinar, hosted and organized by the DSA and CERAD with support from Nordic regulatory authorities.

1.2 Objectives and topics of interest

The objective of the joint workshop was to explore approaches to building a coherent risk and safety assessment framework supporting regulatory supervision for decommissioning and waste management, including all challenges related to legacy problems and to support the development of assessment methodologies and a relevant framework from a multidisciplinary perspective. To achieve this, the workshop aimed to bring together regulators and scientific experts in radiological protection, waste management, decommissioning, and legacy management, with a focus on research and radiation facilities in the Nordic countries, in order to:

- share knowledge and experience in addressing coherent risk and safety assessments, the application of optimization and related regulatory decision making.
- increase awareness and promote collaboration within the Nordic countries.
- identify key challenges and scientific and research issues related to decommissioning and waste disposal safety and risk assessments for nuclear research and radiation facilities and sites, both internationally and from a Nordic perspective; and
- identify key needs and common gaps as the basis for recommendations for future work on how to regulate and practically implement collective knowledge in these fields.

Key topics of interest for the workshop were as follows:

- Lessons learned from legacy sites, decommissioning, and waste management experiences, including experience in regulatory review of license applications and safety assessments (for relevant facilities).
- Experience in the selection of reference levels, constraints and other criteria for control of risks to people and the environment.

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2 https://www.oecd-nea.org/jcms/pl_39653/new-nea-expert-groups-on-decommissioning-and-legacy-management

- Radiological and other risk assessment methods that support proportionate and optimized management of different hazards and risks to workers, members of the public and the environment as represented by populations of relevant biota.
- How to implement a holistic / multi-risk / graded approach to:
    - identify relevant protection objectives for appropriate management end points, and the corresponding risk and safety assessment endpoints.
    - balance the management of radiological protection and other risks linked to the construction, operation and closure of radioactive waste repositories.
    - develop consistent and coherent short-, medium- and long-term methods for delivering overall optimization in decommissioning and radioactive waste management.
- Identification of key scientific uncertainties that affect safety assessment based on practical examples.
- Sharing of research conducted to reduce those scientific uncertainties, including methods and results for improved:
    - waste characterization from a waste and materials end state perspective.
    - site characterization to support decisions of remediation techniques, and suitability of location for treatment, storage and disposal, noting that, in the case of contaminated land and possible in situ disposal, the site is the waste.
- Identification of continuing challenges and the scope for them to be addressed by future research projects.
- Sharing of experience on risk communication.

These issues are relevant to Nordic authorities, organizations, industries and university departments that are, or will be, involved in risk and safety assessments for the decommissioning of nuclear objects and sites and management of radioactive waste. The workshop aimed to provide an opportunity for knowledge transfer among participating groups, thereby contributing to increased competence and collaboration, identify relevant research opportunities.

1.3 Participation and programme of the workshop

Participation included Nordic regulators, operators, scientific and technical support organizations and other stakeholders with an interest in nuclear and radiation scientific research and support for decommissioning, waste management and legacy management, including experts within the fields of risk assessment and radioecology. The full list of participants and their affiliations is provided in Appendix A, comprising 54 people representing operators and regulators, technical support organisations and academic institutions.

The workshop was organized as a webinar over three days covering the following topical areas:

1. **Experience**: Encompassing lessons learned from legacy sites, decommissioning and waste management experience; experience in the selection of reference levels, constraints and other criteria for control of risks to people and the environment; and implementation of holistic/multi-risk/graded approaches.
2. **Methodology**: Radiological and other risk assessment methods that support proportionate and optimized management of different hazards and risks to workers, members of the public and the environment and identification of key scientific uncertainties that affect safety assessment based on practical examples.
3. **Challenges**: Sharing of research conducted to reduce scientific uncertainties, including methods and results for improved waste characterization, site characterization,

identification of continuing challenges and the scope for them to be addressed through research, and sharing of experience of risk communication.

A series of presentations was provided in each of the topical areas. Group discussion sessions were also organized, aimed at eliciting input and views from as many participants as reasonably achievable, with participants being divided into four groups. Each group was provided with the following questions to discuss:

- What are the key contaminants (both radioactive and non-radioactive) from research facility decommissioning and what makes them key?
- What environmental media / exposure pathways are important for these key contaminants?
- What site characterization data are important?
- Are the answers different for operations and for releases in the long-term future (e.g. from repositories)?

The report is structured in line with the workshop programme, with sections 2 to 4 providing summaries of the presentations and discussion in the sessions on experience, methodology and challenges; section 5 setting out the key results from the four break-out discussion groups, and section 6 then provides overall conclusions and recommendations.

The report was drafted by DSA and reviewed by participants for correctness prior to publication.

2 Session 1: Experience

Session 1 focused on experience and lessons learned from legacy sites, decommissioning and waste management, including regulatory review of license applications and safety assessments for relevant facilities.

2.1 Introduction to the Nordic workshop on “Risk and Safety Assessments Supporting Regulatory Supervision of Decommissioning and Waste Management for Nuclear Research and Radiation Facilities”

Malgorzata Sneve (DSA, Norway) and Ole Christian Lind (CERAD and Norwegian University of Life Sciences, Norway) presented.

2.1.1 Background, scope and expectations

Norway, Denmark, Sweden and Finland all have a nuclear research history with research in nuclear technology development resulting in legacy sites, facilities and wastes. The countries have cooperated in nuclear and radiation safety and share a common understanding of the role of safety assessments to demonstrate compliance with protection objectives. Common challenges are also faced in addressing the uncertainties linked to those assessments.

Such challenges have been recognized internationally for some time with activities being undertaken to address the key challenges faced. For example, the NEA has produced a series of reports on the management of legacy sites (NEA, 2016; 2019; and in press), DSA has organized a series of workshops on the topic (e.g. Sneve, 2020) and the International Atomic Energy Agency (IAEA) and international BIOPROTA forum have recently undertaken a joint programme on enhancing a methodology on dose assessment for releases from radioactive waste repositories (interim report at SKB, (2018)). Whilst there have been considerable activities undertaken to date, there remains scope for further development of Nordic cooperation on common interest areas in this field since the Nordic countries share a common geography and characteristics, including economics.

Much can be learned from reviewing safety cases and assessments, including the key issues and uncertainties identified by operators and regulators. It is important to reduce the key uncertainties that impact on the ability to make robust decisions and the development of understanding of those key uncertainties requires close engagement and dialogue between researchers, operators and regulators, as well as other affected stakeholders. It is important, therefore, to share safety assessment reports and conclusions of reviews to inform on what are the key uncertainties affecting regulatory decision-making.

This workshop has therefore been organized around the following objectives:

- → explore approaches to building a coherent risk and safety assessment framework;
- → identify key scientific uncertainties in safety assessments for decommissioning and waste disposal safety, especially from a Nordic perspective;
- → share research results and develop proposals to reduce uncertainties; and
- → share experience to improve risk communication.

Some key radionuclides and radionuclide-specific parameters are already known. For example, Co-60, Sr-90 and Cs-137 are important for operations whereas for long-term safety assessments for radioactive waste disposal the key radionuclides are commonly H-3, C-14, Cl-36, Se-79, Mo-93, Nb-94, Tc-99, Ag-108m, I-129, and Np-237, most of which are difficult to measure and some (e.g. C-14, Cl-36 and Se-79) need radionuclide specific models to account for their behavior in the environment3. It is not just radionuclides that need to be taken into account, however. Chemical hazards such as arsenic, beryllium, lead and uranium (which poses both radioactive and a chemotoxic hazards) may be present in wastes (BIOPROTA, 2015). Radioactively contaminated asbestos is another important management challenge in reactor decommissioning[4]. The provision of adequate information and reliable data, for use both in the design of assessment contexts and in model development and parameterization, is another important area for consideration. It is relevant to discuss how site characterization and site understanding can be used to provide such information, noting that relevant input can be provided from many sources. It is important to ensure good dialogue between operators, regulators, scientific communities and affected stakeholders interested in the issues, to ensure that the correct questions are asked that address those issues and thereby support and justify decisions. Involvement of a broad range of stakeholders from the beginning of the assessment process also helps the processes of communicating what can be quite complex assessment results.

The workshop was very ambitious in scope and it was not possible to discuss all of the important aspects in detail. However, common interests and specific needs can be identified, and it was hoped that discussion around those issues and needs would point to important research topics for which joint projects could be developed to the mutual benefit of all the Nordic countries. A key objective was therefore to develop a provisional list of topics that could benefit from further research and investigation.

2.1.2 Science supporting nuclear decommissioning, legacy and waste management

The Centre of Environmental Radioactivity (CERAD CoE) receives long-term funding under the Centre of Excellence (CoE) scheme of the Norwegian Research Council and performs basic research to improve the ability to accurately assess the radiological risks from environmental radioactivity combined with other stressors. By focusing on key factors contributing to the uncertainties, CERAD represents a state-of-the art research foundation for the advancement of tools and methods to better manage those risks. The scope includes man-made and naturally occurring radionuclides that were released in the past, those presently released, and those that potentially can be released in the future from the nuclear fuel cycle and from non-nuclear industries. Using an ecosystem based scientific approach, CERAD focuses on different source term and release scenarios, transfer of radionuclides in terrestrial and aquatic ecosystems, biological responses in organisms exposed to radiation combined with other stressors such as metals and UV radiation under varying temperature/climate conditions, to assess overall environmental impact and risks. CERAD research covers a broad scientific field and the assessments include possible impact not only on man and non-human organisms, but also economic and societal consequences. The program is based on the interdisciplinary effort from scientists representing five Norwegian organisations (NMBU, NRPA, MET, NIPH, NIVA) and a network of international specialists.

CERAD is performing cutting-edge research thanks to unique experimental facilities, models and tools within CERAD/NMBU's own premises and through collaboration with Norwegian partners and international institutions. There is extensive international collaboration, including field work at different contaminated sites around the world.

The decision to close down the Norwegian research reactor in Halden, will lead to a large demand of competence on nuclear reactor dismantlement and nuclear waste management in Norway, for years to come. CERAD CoE aims to contribute to meeting some of those demands. The potential accidents and

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3 See Bytwerk et al (2011) in the case of Cl-36 and www.bioprota.org for further examples.

[4] See for example, various presentations from the 18th European Alara Network workshop on 18th Workshop: ALARA in Decommissioning and Site Remediation, available at https://www.eu-alara.net/index.php/activities/workshops/322-18th-workshop-alara-in-decommissioning-and-site-remediation.html

releases associated with decommissioning would call for radioecological competence and advanced radioecological models that could be offered by the CERAD consortium.

It is important to recognize that models are simplified representations of reality and are often associated with large uncertainties. Research is needed to characterize and reduce those uncertainties. Furthermore, source terms can be complex and many processes influencing ecosystem transfer and the presence of a multitude of stressors will influence biological responses in exposed organisms. The organisms that are exposed also have different sensitive life stages that need to be taken into account. Problems around variability, questionable assumptions and knowledge gaps also contribute to uncertainties and it is important to be able to identify the key variables, parameters and processes contributing most to the overall uncertainties in order to prioritize research topics. This can be achieved for example through model sensitivity analysis.

2.2 Potential challenges in future decommissioning of Norwegian nuclear facilities

Marte Holmstrand (DSA, Norway) presented.

The current operator for Norwegian nuclear facilities is the Institute for Energy Technology (IFE), but in the future the operator will be Norwegian Nuclear Decommissioning (NND). The regulatory authority for nuclear and radiation safety is DSA. The current status for decommissioning plans for the nuclear facilities is that they are ongoing and, currently, the facilities are in a transitional decommissioning phase.

There are three nuclear sites in Norway – IFE Halden, IFE Kjeller and IFE Himdalen. IFE Halden is comprised of a heavy-water boiling water reactor (HBWR), storage facilities and a fuel instrumentation workshop. The IFE Kjeller site is home to the JEEP II research reactor, several storage facilities, a radioactive waste facility as well as two partially decommissioned research reactors (JEEP I and NORA) and laboratories. IFE Himdalen is a combined storage and disposal facility for radioactive waste.

The research reactors were unexpectedly shutdown due to technical (a failed valve in HBWR and corrosion in JEEP II) and financial reasons. Fuel is still within the HBWR. As a result of the unexpected shutdown, there is a need for a rapid maturation of the decommissioning mind frame. The level and quality of information on the reactors and facilities is lacking and the decommissioning of the JEEP I and NORA reactors has not been completed in line with today’s standards.

The nuclear facilities are up to 60 years old and for some facilities it is difficult to prove that they are safe enough for extended life. For example, there is water ingress into some of the spent fuel storage facilities. For some facilities, updates need to be made and new facilities for radioactive waste management are required, including new storage facilities for spent fuel and for packaging spent fuel.

The regulatory framework should in connection with the new phase be revied and guidelines should be developed. Issues include free release criteria and guidance documents setting out criteria for decommissioning plans and other matters connected with compliance with license conditions. Consideration also needs to be given to the transfer of ownership and licenses from IFE to NND. The Planning and Building Act, also needs to be considered.

Good mapping of areas is required, and criteria need to be assessed for strategies for mapping areas, such as sampling methods, number of samples and radionuclides to be monitored. Whilst the Norwegian facilities are small, they encompass all the complexities associated with the entire fuel cycle from production to disposal and, with them being old, information is often lacking. Ground contamination is expected at the sites, along with building contamination and mapping needs to be undertaken.

Waste characterization is also required. A significant increase in waste generation is expected once decommissioning starts. The types of waste generated will also vary. Repositories are expensive and wastes therefore need to be segregated to optimize waste consignments. This requires sampling methods and criteria that are pragmatic and robust to allow wastes to be appropriately characterized. Many wastes, however, contain difficult to measure radionuclides or the radionuclides may be heterogeneously distributed, creating issues for waste characterization. Some waste streams may be difficult to handle, for example organic liquids containing plutonium. Other wastes may be excluded from disposal due to legal constraints, such as liquids that cannot be discharged or organic wastes contaminated with radionuclides. Non-radioactive wastes may also be refused by conventional waste disposal facility operators due to concerns that they could be radioactively contaminated.

Demolition techniques for nuclear facilities tend to be reliant on some level of manual labour and more automated techniques are required to reduce worker doses. Criteria for verification of the proposed dismantling methods and the dismantling itself according to licensed procedures are also required. Criteria for verification of decontamination methods and techniques are also needed.

Assessments for new repositories will require assessment criteria for a safety case and geological assessments to be undertaken that are sufficient for a repository, the design of which could be deep geological disposal or borehole disposal. Waste acceptance criteria will also be required.

The spent fuel inventory in Norway from research reactors is of low volume as compared to that for conventional nuclear power plants but has a diverse burn-up history. There is a need to investigate different options and compare them, and in order in due course, identify the preferred safe option. There are significant uncertainties and it is appropriate to consider many options in parallel, in order to secure an environmentally sound solution, based on a holistic assessment of available treatment options. In selecting the treatment option that creates a waste form suitable for disposal, it is also necessary to consider the risks associated with the treatment process itself. However, the spent fuel is not currently well characterized to allow such an assessment to be performed and to demonstrate that safety limits will be met.

Radiological surveys for verification of radiological characterization procedures and results are needed, which may require support from consultants and technical support organizations. A final task of decommissioning is a final radiological survey and criteria will need to be established by DSA for verification of these surveys.

2.2.1 Discussion

The biggest challenge faced is the characterization of spent nuclear fuel. Such characterization is required to support decisions around handling and treatment options and to support removal from its present locations. Currently there is insufficient information on the inventory and a lack of storage options. Concepts for radioactive waste disposal, which are in initial stages of development, therefore need to be progressed.

2.3 SSM's experience from the decommissioning of the Studsvik materials testing reactors

Leif Jonasson (SSM, Sweden) presented.

There are three licensees present on the Studsvik site: Cyclife involved in radioactive waste treatment, Studsvik Nuclear involved in research and Svafo, the licensee for the materials testing reactor complex.

Historic legacy wastes are present on the site and the research reactor complex consists of two reactors. Reactor R2-0 is a 1 MW pool type reactor that is movable and convection cooled. R2 is a 50MW reactor that was operational from 1960 to 2005.

The regulatory framework for decommissioning of the R2 reactor consists of two central documents (SSMFS 2018:1 and SSMFS 2008:1, Chapter 9). A decommissioning plan and safety analysis have to be submitted for formal approval by SSM with work package notifications (WPNs) and reports then being submitted for review for regulatory oversight of planned work programmes. The regulatory framework had not been tested in practice prior to the R2 decommissioning project.

The regulatory framework for decommissioning was updated in 2012 and the first documents from the licensee were submitted in 2013. These included a decommissioning plan, a waste management plan for the decommissioning project and a safety analysis report. SSM is also continuously updated on the work being undertaken through WPNs.

Following shutdown of the R2 reactor in 2005, defueling was completed in 2006 with fuel being shipped to the United States (US). Svafo became the licensee for the reactor complex in 2010 and preliminary planning and radiological characterization activities were initiated, but other decommissioning projects had higher priority, such as building a facility for stabilizing plutonium for long-term storage and the transportation of plutonium stored at Studsvik to the US. These projects were completed in 2012.

In 2012, a decommissioning project was relaunched by Svafo to develop a waste management plan and decommissioning plan and a safety analysis report for decommissioning was presented to SSM in 2013 for approval. Decommissioning activities were divided into three main stages:

1. Segmentation of reactors (2014-2016);
2. Removal of biological shield and connected systems (2016-2018); and
3. Handling of remaining contaminated systems and components in the R2 complex (ongoing).

Stages 1 and 2 were associated with the majority of the nuclear inventory. As such, it would be expected that these would be the most challenging in terms of making a safety case. It was actually relatively easy, however, to make the safety case as a result of having a good inventory of the radioactivity associated with the fuel ponds and biological shields. The stage 2 strategy was to remove activated and contaminated material and then release the remaining structures as part of the reactor building. Controlled ventilation was in place to avoid the spread of contamination and demolition was achieved using remotely operated equipment

Stage 3 proved to be the most challenging due to historical buildings and poorly documented history. It has been necessary therefore to go through each building and trace the history of activities and characterize the inventory and contaminated structures. Work packages have been implemented to address unique situations and work toward the development of documentation for SSM to review prior to works being carried out. Work is expected to be completed in 2021 with submissions for the release of buildings being handed in.

R2 decommissioning has been ongoing for 10 years and has been a learning experience both for SSM and the operator. Dialogue between the licence holder and SSM has been necessary throughout to develop the scope of preparatory activities, balancing and prioritizing tasks and agreeing the scope of work package notifications. The experience has also helped in developing an understanding of the information requirements necessary to support decision-making as to whether radioactive waste management is consistent with regulations. One of the key lessons learned has been to manage information needs and to balance what is necessary in the early stages to allow progress and that which can be developed as the decommissioning programme progresses, ensuring the regulator receives all necessary information throughout the process. The lessons learned have led to the implementation of additional licensing conditions for decommissioning of nuclear power plants, first issued in 2017.

2.3.1 Discussion

It is common for there to be a lack of information on early operations at sites that have been operational for many years. Characterization of buildings and facilities is therefore often required but can be combined with other approaches to develop the necessary information base, including interviewing employees to build an understanding of past activities.

The process of decommissioning old facilities is time consuming and challenging. An iterative process is needed with good interaction between the operator and regulator to develop the necessary information base to support decision-making. The key stakeholders for the Studsvik reactors decommissioning project were SSM as the regulator and Svafo as the operator. There was also an environmental process that was outwith SSM's mandate.

2.4 Development of SSM's authorization for dismantling and demolition of nuclear reactors

Martin Amft (SSM, Sweden) presented.

There are several nuclear sites throughout Sweden, including several operational nuclear power plants (NPPs), a central interim storage facility for spent nuclear fuel (SNF) and a final repository for short-lived radioactive waste. There are also five NPPs and one former uranium mining and milling facility that are under decommissioning.

The decommissioning strategy for NPPs following shutdown is immediate dismantling, as set by the Radiation Protection Act. Within 18 to 24 months following shutdown, nuclear fuel, control rods and core instrumentation are transferred to SKBs interim storage facility. This is not a formal requirement but is considered good practice. Low and intermediate level wastes generated as a result of decommissioning are temporarily stored on each NPP site, pending disposal at repositories operated by the Swedish Nuclear Fuel and Waste Management Company (SKB). Dismantling and demolition (D&D) activities begin with 'hot' and progress to 'cold' systems and structures. Exceptions include 'cold' systems that are closely connected to 'hot' systems. The planned site end state is industrial use or energy production.

The D&D of NPPs requires three authorizations:

1. A new license according to the Environmental Code, issues by the regional Land and Environmental Court;
2. SSMs approval of a safety analysis report (SAR) for dismantling and demolition; and
3. SSMs approval of a radiological environmental monitoring programme.

The generic regulatory framework for decommissioning is illustrated in Figure 1. There are three phases to decommissioning. The first is the removal of nuclear fuel. This is followed by a non-mandatory care and maintenance phase, for which a SAR is required. A further SAR is required for the final D&D phase. The SAR has to be approved by SSM before D&D can progress.

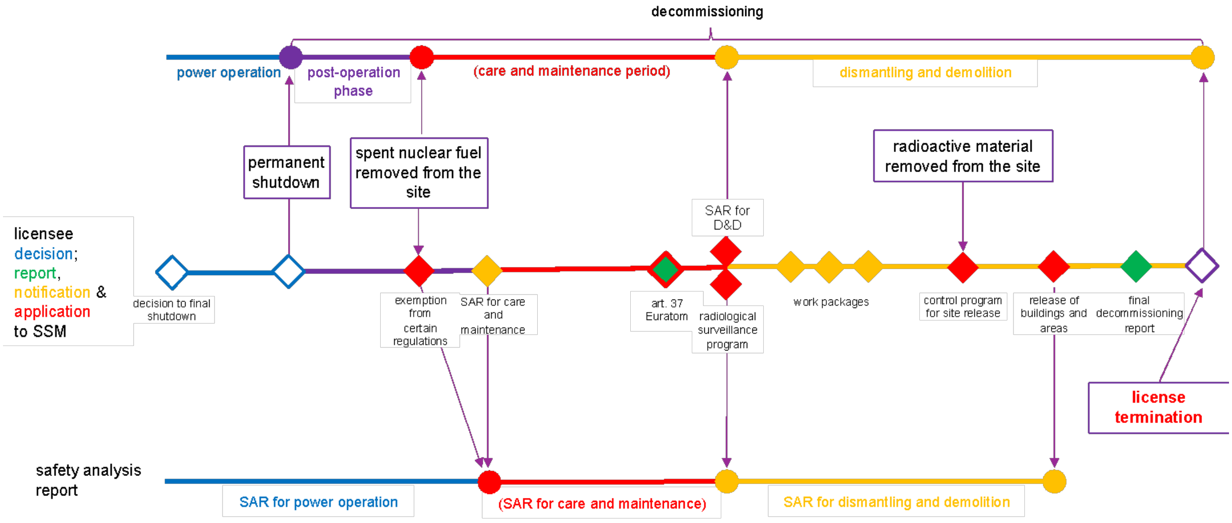

Figure 1 SSM's generic regulatory framework for decommissioning.

Additional licence conditions for the decommissioning of NPPs are connected to the SAR and work package notifications and replace or supplement existing requirements in SSM's regulations. They specify requirements for the preparatory measures to be taken, the content of the SAR for D&D, operational limits and conditions, authorized discharges and environmental control, and the content of the final decommissioning plan and work package notifications and associated reports. SSM approval is needed for all measures following the permanent shutdown to dismantle or demolish activated or contaminated systems, structures or components. There are, however, 16 accepted preparatory activities specified in the additional licence conditions to facilitate safety and security and radiological protection. These include SNF removal, drainage of systems and measures for radiological characterization.

The D&D documents that are approved by SSM include the SAR, operating license conditions, waste management documentation and the radiological surveillance programme. A decommissioning plan and decommissioning strategy are also required, but are not subject to formal approval by SSM. In developing the strategy for regulatory review of applications, SSM took into account international experience, particularly from Germany and Switzerland, adapting as appropriate to the Swedish situation. The review covers all aspects falling within the regulatory framework, including:

→ Integrated management system;
→ Planned D&D measures;
→ Radiological characterization;
→ Waste management, treatment, logistics, and interim storage;
→ Safety analysis;
→ Radiation protection and radioactive discharges;
→ Nuclear security; and
→ Emergency preparation.

Licensees formally divide the programme into around 12 work packages per reactor. These work packages provide supplementary information to the SAR and other approved documents and/or to the final decommissioning plan. Work package notifications specify the scope of the work packages and their time schedules, supplement, if necessary, the previously approved SAR, operational limits and conditions or waste management documentation, describe the D&D measures in more detail than in the final decommissioning plan and specify any additional radiation protection, safety and/or security measures. The notifications also detail all contractors involved in implementing the D&D measures. SSM then builds supervision activities around the work package notifications, following the preparation of work packages on a regular basis through regular meetings and surveillance inspections. Generally, the supervision of work packages involves three steps. On-site surveillance inspections are held during the preparation of the work package and during the set-up of equipment to meet contractors. Work package notifications are then assessed and follow-up on-site inspections are made as the work progresses.

SSM is formally notified of any work package four weeks before activities are planned to commence. Following an initial assessment, SSM then decides whether activities can commence with no further assessment, activities can commence with further assessment or activities cannot progress until SSM has fully assessed the notification. To date, the latter decision has not been made.

SSM's regulatory framework for decommissioning has proved to be robust and sufficiently flexible and the authorization process for D&D is effective. To date, the supervision of the implementation of work packages has been successful, but the number of work packages that are progressing in parallel at different sites leads to challenges from a resource perspective.

2.5 Release (removal) of non-contaminated and non-activated material from nuclear facilities in Sweden

Martin Amft (SSM, Sweden) presented.

Around 90% of decommissioning waste from Swedish NPPs is forecast to be zero-grade conventional waste (Figure 2). Such waste needs to be distinguished from waste requiring clearance, where clearance is the process for proving that the radiation protection law does not apply as the radiological risk is negligible. Release is then the process to show that the radiation protection law is not applicable and that material can be released without the need to follow a clearance process. Such released materials should not come from controlled areas and should not be contaminated or activated.

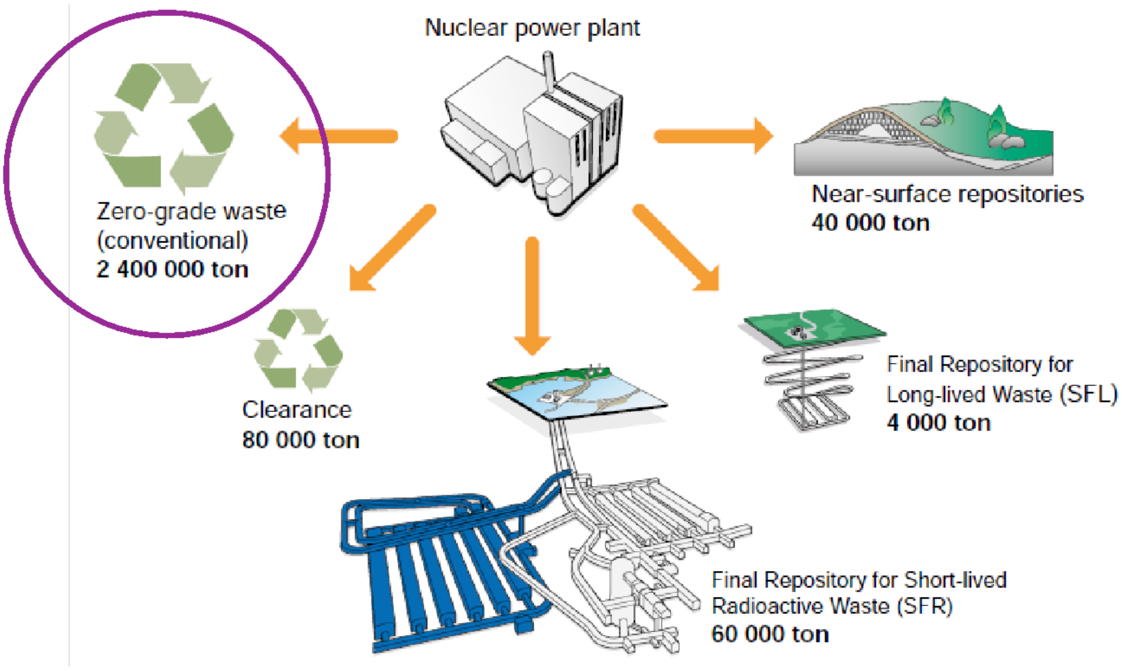

Figure 2 SKB forecast of waste generation from the decommissioning of Swedish NPPs.

SKB report R-16-13 (translated to English in report R-17-05[5]) sets out four risk categories for wastes generated as a result of D&D of facilities:

1. Extremely low risk of contamination
2. Low risk of contamination
3. Risk of contamination
4. Contamination over clearance levels

All material falling in category four is required to be disposed of in a suitable waste repository. Category 3 wastes may be routed to a repository and Category 2 wastes may be suitable for clearance. The wastes in Category 1 are essentially conventional wastes.

The operator of the Barsebäck NPP in Sweden (Barsebäck Kraft AB (BKAB)) has developed a process to identify and manage objects belonging to the extremely low risk of contamination category, as illustrated in Figure 3. During the first stage, the question is asked as to whether the object is known to have been historically contaminated or activated? If the answer is no, confirmatory measurements are made. If results of measurements show contamination levels are less than 10% of the clearance level, the object can be formally released. Release is required to be appropriately managed to ensure contamination does not occur during the process.

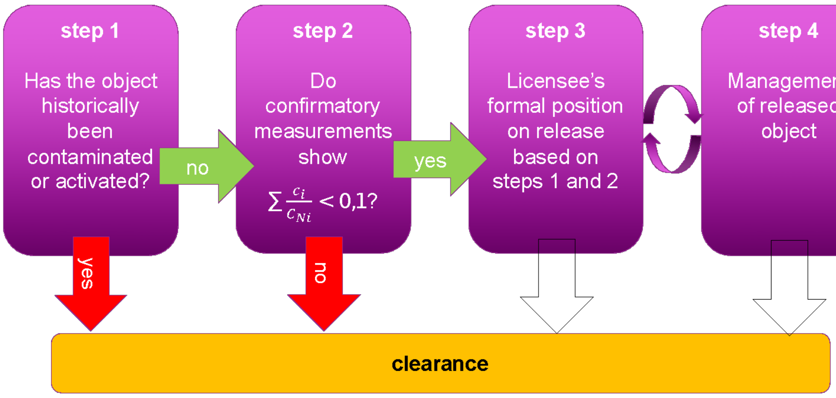

Figure 3 BKAB's process for release of objects.

Following a formal review of the process in 2020, SSM concluded that the BKAB process for release of objects as good practice and suggested other Swedish licensees develop a similar process. There is no formal requirement for such a process but it makes sense to promote the identification of waste materials that can be managed as zero-grade conventional waste, and thereby allowing focus of regulatory attention where it is required.

BKAB has applied the process to parts of a storage building, allowing the building to be demolished in 2020 in order to construct a new interim storage facility for very low-level waste. Water treatment facility and hydrogen facility equipment has also been sold following application of the release process. Current issues remain, however. For example, it is not possible to release areas of nuclear sites since, according to regulations, areas must be cleared. Therefore, where buildings are released and subsequently demolished, the ground below the building cannot be released. However, ground below a paved area that has been cleared according to the regulations could be released if it is demonstrated that the pavement itself hasn't been contaminated. It should be recognized, however, that contamination can spread and may not occur only from above and this should be taken into account. The question of release of below ground material is therefore a work in progress.

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[5] Available at https://www.skb.com/publications/

2.6 Review of the final decommissioning report for the Ranstad site

Heléne Wijk (SSM, Sweden) presented.

The Ranstad site was a uranium mining and milling plant that was established in 1960. It was initially state owned but changed ownership over time. Since 1987 the site has been under the ownership of Ranstad Industricenctrum AB (RIC). The site is located in Sweden between two large lakes.

During operations, most mining activities were done in an open pit that has since been transformed into a lake (Tranebärssjön). Between 1965 and 1969, around 200 tonnes of uranium were produced from alum shale ore and milling tailings were deposited close to the Ranstad industrial area. The tailings area drains to smaller lakes (Figure 4). Mining ceased in 1969 for economic reasons. From 1970 until 1982, the Ranstad facility was used for research and development projects. Between 1982 and 2009, the site was used for uranium recovery from nuclear fuel fabrication waste. In 2009, the facility was formally closed and the legal permit ended. Decommissioning has been undertaken in several steps since this time.

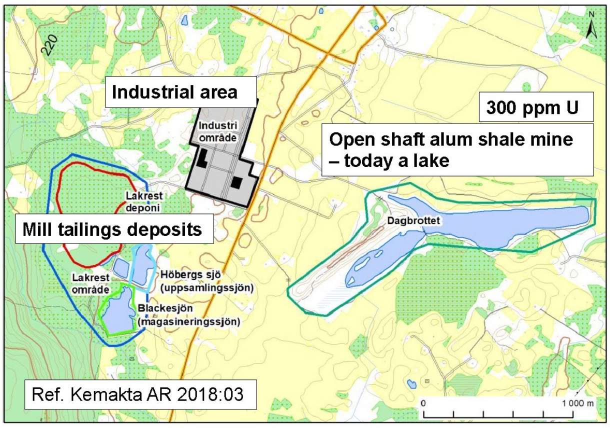

Figure 4 Areas of the Ranstad uranium mining and milling facility.

There has been good cooperation between county officials and SSM during the more than 10 years of decommissioning at the site. The County Administration Board has legal demands for a final report after final environmental remediation measures are completed. In 2017, the main buildings at the site were demolished leaving only an industrial area. Much of the area is now grassland or woodland.

The regulations SSMFS 2008:1 require a decommissioning report to be submitted to SSM following completion of decommissioning. The report is required to include a description of the implementation of decommissioning, experiences and the final condition of the facility. General advice in support of the regulations also advises licensees to report on how nuclear material in the facility and radioactive waste from operations and decommissioning have been disposed of. The disposal of non-radioactive waste from dismantling and demolition should also be reported.

In discussing the content of the final decommissioning report with RIC, it was established that the regulations did not provide sufficient information on the content and level of detail required for the report and the regulations were considered inadequate. There was a need to ask RIC to complete the decommissioning report with additional information detailing the history of the facility and the different activities and operations that had been conducted on the premises as well as a description of earlier steps taken to decommission the site by other licensees/responsible companies. Further information on discharges and environmental monitoring during and after operations, radiation protection of workers, remaining environmental impact on premises and surroundings was also required, along with a description of clearance procedures and total costs for decommissioning.

The decommissioning report for the Ranstad site is the first such report to have been developed so it has been a development project with the report being checked, discussed and reviewed several times before completion by RIC. The full report, incorporating all the requirements and suggestions outlined above, was submitted to SSM in December 2020.

As a result of the close interaction throughout the development of the report, SSM was aware of the content and the review has been completed. The report is considered a good example for other licensees in the process of decommissioning. SSM now needs to further develop the regulations to take account of the experience gained and this work is in progress.

2.6.1 Discussion

The relevant authorities (SSM and the County Administration Board) have closely collaborated in Sweden to address the different contaminants present at the site. Regular meetings were held to ensure close cooperation, and this worked well throughout the process to ensure the different risks and hazards were managed.

Tailings remain an issue at the site. The tailings are considered more toxic than the original shale and there is the potential for migration of contamination. As such, they have not been released from regulatory control. They were covered in the 1990s and the County Administration Board has introduced a special environmental arrangement around the tailings to restrict land use and regular monitoring is conducted. Whilst the County Administration Board is the responsible authority, SSM assists. The tailings are currently stable, but a solution for the future will be needed. Monitoring has identified some groundwater contamination, but the level of contamination is low and migration slow.

3 Session 2: Methodology

Session 2 focused on radiological and other risk assessment methods that support proportionate and optimized management of different hazards and risks to workers, members of the public and the environment, and the identification of key scientific uncertainties affecting safety assessment based on practical examples.

3.1 Clearance of the Ranstad site (former uranium mining and milling facility)

Henrik Efraimsson (SSM, Sweden) presented.

The Ranstad former uranium mining and milling facility in Sweden is equidistant to Oslo, Stockholm and Copenhagen. During operations, the open shaft mine provided up to 300 ppm uranium that was processed in an industrial area (see Figure 4 in Section 2.6). During remedial activities over the last 10 years, old buildings, contaminated from early activities at the site, were removed and waste from a former dump site was removed to a conventional waste site. In the early 1990s, when the open shaft mine was restored to a lake, the mill tailings were covered and secured to prevent leakage.

A national aerial gamma radiation survey was undertaken in 2003. The results indicate some elevated radiation at the site (around 40 ppm uranium) but the levels are much lower than at nearby areas associated with the remains of burnt alum shales from historical processing for heating and industrial purposes where up to 100 ppm uranium was recorded.

The Ranstad site was a real industrial complex prior to decommissioning. A leaching facility was present where crushed shales were mixed with acid and the facilities were associated with large amounts of concrete and steel pipes. When demolition works were undertaken in 2017, contaminated sludges in pools had to be managed. The sludges were classed as radioactive waste.

In 2019, there was around 370 tonnes of uranium contamination remaining at the site, as illustrated in Figure 5. The majority of the uranium remaining, around 220 tonnes, is associated with the disposal of tailings. Half of the uranium in the shales was extracted during their processing and half remained in the tailings. Piles of uranium shales that have not been processed remain close to the lake and it is the uranium associated with these piles that was detected in the aerial gamma radiation survey that was undertaken in 2003. The background in the area is around 5 ppm uranium whereas these piles have a concentration of around 100 ppm uranium.

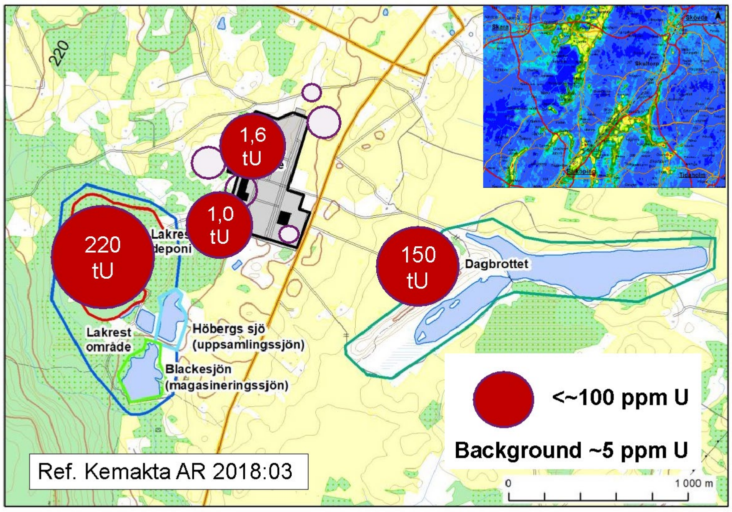

Figure 5 Remaining contamination in 2019 at the Ranstad site.

In the 2018 regulations for the release of sites, a criterion of 100 μSv/y to any member of the public, with or without restrictions on the future use of the site is given. If restrictions are violated or cease to be in force, a maximum criterion of 1 mSv/y applies. Two areas with restrictions were decided upon by the County Administrative Board, based on contamination levels. Within these areas, the drilling of wells is restricted due to groundwater contamination.

SSM has concluded that all contaminated areas have been identified to the extent that can reasonably be required and contaminated areas have been cleaned as far as reasonably achievable. Calculated future radiation doses to the public are less than 100 μSv/y with only permanent occupancy with farming yielding a dose above this criterion. If restrictions on land use were to fail, calculated doses would be about 1 mSv/y.

The overall judgement from SSM was, therefore, that the Ranstad site could be released from regulatory control if

- → intrusion in the most contaminated soil and groundwater could be prevented, which is achieved through the County Administration Board land use restrictions;
- → if awareness of radon risks was enhanced; and
- → if the higher risk of a permanent resident farmer was communicated to local inhabitants, recognizing that natural background radiation in the region was broadly consistent with the doses calculated.

It was therefore concluded that clearance of the site would not impose an unacceptable risk of harmful radiation effects on people or the environment and the condition for clearance from regulatory control according to the Radiation Protection Act was deemed to have been met. It was necessary, however, to deviate from well-established principles for radioactive waste management in order to achieve clearance of the site.

The licensee has taken all reasonably required measures to decommission the site and, in 2019, the former open shaft mine and the industrial area were released from SSM's regulatory control according to the Act on Nuclear Activities and the Radiation Protection Act. Chemical contamination aspects of the uranium mine are subject to the Environmental Code which does not have such release conditions. Further remediation may still be needed to address residual chemical contamination.

3.1.1 Discussion

The different regulators worked together, but joint regulations were not developed. Decisions were however coordinated where appropriate with regular project meetings taking place between SSM and the County Administration. Often, the County Administration made recommendations that were then reviewed and considered by SSM. Through the close cooperation it was possible to achieve a good solution for the site.

3.2 The safety evaluation of a low level and intermediate long-lived nuclear waste repository (SFL)

Ulrik Kautsky (SKB, Sweden) presented.

SKB is the organization responsible for radioactive wastes in Sweden. The majority of wastes arise from nuclear power plants. A licence submission has been made by SKB for a repository for SNF and a decision is awaited. A repository for short-lived radioactive waste (SFR) is operational. A further repository (SFL) is planned for long-lived low- and intermediate level waste arising from NPPs. The SFL repository will also be used for the disposal of legacy wastes.

Decommissioning of NPPs will generate a lot of radioactive waste compared to other waste streams but the wastes will be well packaged and there will be good knowledge about the content of waste packages. This is in contrast to the legacy wastes to be disposed of in the SFL repository. The legacy wastes were originally intended to be dumped in the Baltic Sea, but anti-dumping legislation prevented this. They include research waste containing liquids, mercury and other hazardous substances. The inventory is not well characterised, however, so the approach has been to consider a worst case of what may be present, based on data that are available.

The suggested SFL repository concept builds on knowledge from previous experience. The concept is for two vaults, one for legacy wases and long-lived waste from Studsvik, hospitals research and industry (BHA vault) and another (BHK vault) for metallic wastes such as core components, reactor vessels and control rods, at a depth of 300 m or more to avoid freezing during future permafrost conditions. The BHK vault will contain more than 98% of repository radioactivity at closure. The wastes will be surrounded by concrete. The BHA vault will contain a greater volume of waste (11,000 m^3 as compared with 5,000 m^3), but less than 2% of the radioactivity at closure. Wastes will be surrounded by bentonite. The safety principles for the repository are to retain radionuclides and retard radionuclide transport.

A safety evaluation has been undertaken and submitted to SSM in 2020. This was not a legal application, but rather an evaluation for repository concept development. The endpoint for the safety evaluation was annual dose to which a criterion of 14 μSv/y applied. Potential effects on the environment were not evaluated. The aim of the assessment was to be as realistic as possible in terms of the model structure, primary transport pathways, landscape development and the associated parameters. As such, an example site was selected for which real site data were available. The evaluation considered the function of the proposed repository concept and the conditions under which the regulatory requirements on post-closure safety would be met. Areas for which additional knowledge would be required to support future assessments were also identified.

Laxemar was chosen as the example site for which there were a lot of site data available, having been subject to characterization as a potential candidate location for the SNF repository. The same conceptual approach to assessment was taken to that used for the SNF repository whereby surface objects consistent with potential geosphere release points were identified, which were consistent with existing or potential future lakes and wetlands and their surrounding local catchment areas. These lakes would, over time, have the potential to become agricultural land that would give rise to the highest potential exposures. The key biosphere object (206) for potential discharges was identified, based on fluxes from the repository to the surface environment, driven by the local hydrogeology (Figure 6).

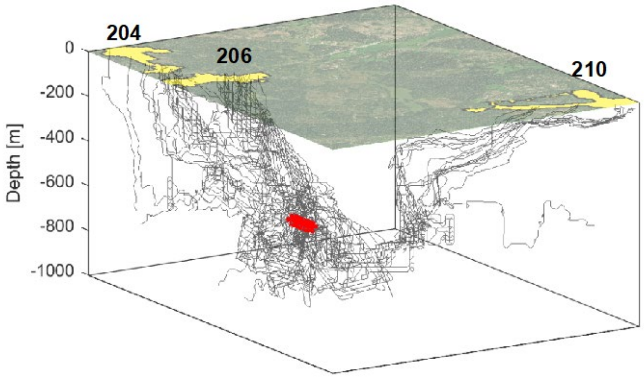

Figure 1 Identification of the key biosphere object (206) from fluxes from the SFL repository to the surface environment.

An integrated modelling approach was applied in the assessment. The biosphere model, implemented in Ecolego, was the same as that used in the most recent safety assessment for SFR, but with some developments to represent the landscape in Laxemar. The conceptual model is illustrated in Figure 7.

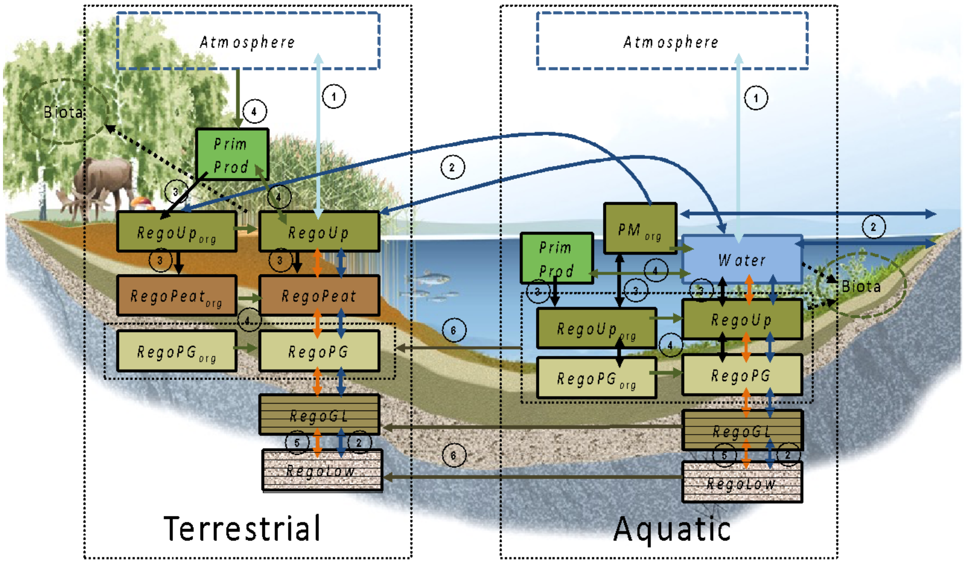

Figure 7 The biosphere model, implemented in Ecolego, and applied in the SFL safety evaluation.

Radionuclides, transported in groundwater through the geosphere, enter the lower Regolith and are then transported through sediments into water where they are available for uptake by biota. Shoreline displacement over time leads to the isolation of lakes and, over time, these can develop into wetlands that may be drained and cultivated. A number of different exposure groups were considered, including hunter-gatherers, users of drained wetlands for agriculture and of garden plots with groundwater being extracted from wells for irrigation purposes.

Results for annual dose to the most exposed group for the base case were above the regulatory limit of 14 μSv/y for both the BHA and BHK vaults. In the case of the BHA vault for legacy wastes, key radionuclides were Mo-93, Cl-36, Tc-99, U-238 decay chain and C-14. For the BHK vault for reactor parts, key radionuclides were Mo-93, C-14, Ni-59 and Ca-41. There were major uncertainties associated with the legacy waste inventory, including the presence of complexing agents, and radionuclides could be released directly from waste packages, but would be retained over time by the bentonite barrier. For the reactor decommissioning wastes, radionuclides would be released slowly as a result of corrosion and, with degradation of the concrete barrier over time, leaching of radionuclides could occur.

The influence of recipient biosphere objects on dose consequences was analyzed by comparison against the base case of biosphere object 206 being the discharge area. Order of magnitude differences in doses were obtained for similar objects in the same landscape. Discharge to sea or lakes would give rise to lower doses.

The safety evaluation provided a valuable training opportunity for new staff with the integrated approach to modelling helping to develop an interdisciplinary understanding. There is still a lot of work to be done for SFL and an important next step will be the development of the inventory. Understanding the site and making use of site data are important aspects of developing the repository concept and siting. No evaluation of impacts on the environment was undertaken in the safety evaluation, but such analyses have been undertaken for previous assessments (e.g. for the SFR and SNF repositories). Dose rates to non-human biota will, however, be evaluated in future 'real' SFL assessments. Non-radioactive toxicants will also require consideration. The same methods can be applied for transport calculations and multi-stressor effects are not considered to pose an issue since doses are so low. The containment achieved through the repository concept will also be very effective in minimizing the exposure of people and biota as compared with other facilities for non-radioactive contaminants. Public participation is also very important and is achieved through the review of different stages of applications, and also through provision of information, hearings and the Environmental Court.

The enhanced BIOMASS approach was utilized in the safety assessment and this proved to be very useful (SKB, 2018). It is important to focus on the entire process rather than specific parts as all aspects are interlinked such that there is continued iteration between the different parts. By taking a holistic view to the methodology, future surprises can be avoided.

Further information on the SFL safety evaluation is available through the following publications, available from www.skb.com/publications:

- → Main report, 2019. Post-closure safety for a proposed repository concept for SFL. Main report for the safety evaluation SE-SFL. SKB TR-19-01.
- → Biosphere synthesis, 2019. Biosphere synthesis for the safety evaluation SE-SFL. SKB TR-19-05.
- → Climate report, 2019. Climate and climate-related issues for the safety evaluation SE-SFL. SKB TR-19-04.
- → FEP report, 2019. Features, events and processes for the safety evaluation SE-SFL. SKB TR-19-02.
- → Initial state report, 2019. Initial state for the repository for the safety evaluation SE-SFL. SKB TR-19-03.
- → Radionuclide transport report, 2019. Radionuclide transport and dose calculations for the safety evaluation SE-SFL. SKB TR-19-06.

3.2.1 Discussion

Handling of uncertainties is necessary at all stages of the process. Most of the safety reports involve justification and management of uncertainties, noting that safety criteria have been set at very low levels (lower than natural background). Complementary considerations are also taken into account to aid communication with stakeholders, for example by placing radiological risk in the context of other risks. It is not possible to estimate all uncertainties and this can be addressed through pessimistic or worst-case scenarios. Where the results from such scenarios are within the applicable safety criteria then reasonable scientific arguments can be made around safety. Regulators also understand the abstract nature of assessments and uncertainties are taken into account when evaluating safety requirements. A pragmatic approach is required that supports decision making.

3.3 Some insights on the meaning of site characteristics to siting of disposal facilities

Ari Ikonen (EnviroCase, Finland) presented.

Siting experience from Nordic and other programmes for the management and disposal of radioactive wastes from nuclear power plants is significantly applicable to waste from nuclear research and radiation facilities, with the same methodological approaches being appropriate. A graded approach is needed that is proportionate to the level of hazard/risk, noting that those hazards/risks may be radiological, environmental and/or societal.

Site characteristics are important for both radiological safety and environmental impacts, but also for societal impacts. Site selection criteria for radiological safety already largely exist in international guidance. Understanding the geology of a potential site is clearly of interest but it is important that characterization activities, such as borehole drilling, do not compromise the containment properties afforded by the geology of a site. Characterization of the surface environment supports the assessment of radiological and other health and environmental impacts of any contaminant releases; and surface features can be the most important factors for local communities and societal impacts as people tend to focus most on things that will impact on their daily lives, such as transport arrangements. It is also important to recognize that perfect sites do not exist but many sites may be good enough to meet regulatory and other requirements.

Geological criteria for nuclear and radiological safety have been formulated in IAEA documents and are reflected in the 2018 Finnish regulatory guide YVL D.5:

- Rock volumes large and cohesive enough
- Favourable to the performance of the engineered barriers
- Supports long-term safety functions
    - Stability and water-tightness of the rock
    - Low groundwater flow
    - Favourable groundwater chemistry
    - Retardation [capacity] of radioactive materials in the rock
    - Protection against natural phenomena and human actions
- “Have other characteristics favourable to the long term safety”
- Not to have factors indicating unsuitability, such as
    - Proximity of exploitable natural resources
    - Abnormally high rock stresses with regard to the strength of the rock
    - Exceptionally high seismic or tectonic activity
    - Exceptionally adverse groundwater characteristics

These criteria also apply to the long-term release of chemically toxic substances, with the possible exception of organics. The containment afforded by geological criteria therefore mitigates impacts from both radioactive and non-radioactive contaminants.

The surface environment can present both beneficial and less beneficial features. Beneficial features would typically disperse any released contaminants such that transfers to people and the environment are reduced. Less beneficial features would include features giving rise to focused releases or accumulation in relevant environmental media that might be easily accessible. Peatlands fall somewhere in the middle, providing good retention of radionuclides, but have the potential to be converted into agricultural land that can give rise to high dose consequences. The presence of some radiologically beneficial features can, however, give rise to challenges. For example, where wide and thick peatland deposits are present, these can impair the ability to fully characterize the geology, but if they are removed in order to aid characterization then the beneficial features are destroyed. Thought also needs to be given as to how long environmental conditions can reasonably be assumed to prevail relative to the period of release from the geosphere and the regulated assessment timeframe.

Typically, present day environmental aspects tend to be of more interest to people than the long-term risks and, if the opposite is the case, then the disposal concept is possibly insufficiently robust. Environmental aspects include noise, dust, drainage waters, traffic, visual effects etc. Land use changes may also be important, noting that these may not be limited only to the disposal facility itself, but also surrounding land during site characterization and construction. It is also recognized from experience that there can be challenges to occupational safety that may need to be taken into account. These factors are typically omitted from consideration during early phases of programmes, but can be show-stoppers later as a result of local residents opposing construction. Some sites may be ‘easier’ than others, but nonetheless it is easier to ensure such factors are considered from the outset through site-specific evaluation of candidate sites within a graded approach to avoid issues arising as the programme develops.

Societal aspects are also important. There can be both positive and negative impacts on the local and wider society that can be wider than just economics. It is therefore important to gain local knowledge and acceptance through stakeholder dialogue/engagement. Information on the disposal programme, such as safety evaluations and assessments as well as information from site characterization programmes can be valuable inputs to stakeholder dialogue. Robust science is needed for credible discussion with stakeholders, along with good communication planning and communication skills. It is also important to approach stakeholder engagement with a positive attitude. Learning from the experience of others can be very useful.

Site criteria developed on the basis of radiological safety are therefore important, but they set only the minimum requirements. Environmental and societal aspects are also important and should not be overlooked even at the very start of programmes. It is important to consider all aspects in a holistic, graded and proportionate manner from an early stage to avoid show-stoppers.

3.4 Safety culture during decommissioning

Marja Ylönen (VTT Technical Research Centre of Finland) presented.

Decommissioning is an important part of the life cycle of a nuclear facility and should be taken into account during the early stages of the facility’s development. It is a complex project involving many activities, including safe maintenance of the plant following shutdown, planning, licensing, physical and radiological characterization, facility and site decontamination and dismantling and the management of materials, contractors and organizational changes. Documents from the IAEA recommend that decommissioning be undertaken immediately following the shutdown of a plant, but this is not always possible for various reasons.

A number of challenges have been identified related to decommissioning. These include:

- Establishing common legislation and guidance;
- Regulatory oversight and decision-making;
- Developing and maintaining competence and motivation of the licensees organization;
- Licensing;
- Financing;
- Final waste disposal;
- Safe and effective waste characterization and clearance;
- Planning and management of site modification and dismantling; and,
- Collaboration and information sharing between stakeholders.

Challenges in decommissioning are relevant from a regulatory perspective as well as for industry and it is beneficial to develop consistency between the licence holder, regulators and other experts with regard to decommissioning phases and the overall context. Different types of competencies are required, including technical competencies for characterization activities etc. as well as human and organizational competencies. The different expertise needs to be integrated in the context of decommissioning.

Decommissioning challenges give rise to demands on regulation. For example, in deciding between immediate versus delayed decommissioning, it is necessary to consider the pros and cons of each approach and develop an understanding of the challenges associated with both. The different phases and activities need to be identified and the necessary competencies maintained and developed throughout the decommissioning process. The transformation from an operational to a decommissioning organization also presents several challenges. It is not always the same operational organization that takes care of decommissioning, an alternative organization may be responsible. Nonetheless, transformation throughout all different stages should be considered. The requires planning and the specification of plans. Regulators should check plans and pose good questions to the licensees. A regulatory strategy is also needed to inform the process and assist in collaboration between the relevant stakeholders. The characterization of radionuclides is a further challenge. Characterization requires technical competencies as well as understanding of when sufficient characterization has been performed to provide an adequate level of knowledge. This is an important part of decision-making and requires collaboration between experts.

Risk assessment is a systematic process for comprehending, expressing and evaluating risk, and safety culture is a tool for identifying organizational and sociotechnical risks. Safety culture therefore supports and complements risk assessment and should be taken into account when considering risks associated with decommissioning.

Safety culture has been defined in many ways including shared assumptions, values, beliefs, understanding and practices in an organization regarding safety. It is important for meeting safety requirements during decommissioning and when trying to increase capacity and resources in organizations to address decommissioning related problems. Safety culture is also important in identifying sociotechnical problems.

VTT has developed a methodology for assessing safety culture, called Design for Integrated Safety Culture (DISC). The model involves 10 organizational functions relevant to safety culture (for example strategic management and hazard management) and six safety culture criteria that consist of safety values that are reflected in daily activities. This provides the framework for evaluating the safety culture in organizations and for different phases of decommissioning. A safety culture questionnaire (TUKU style) has also been developed with variants for nuclear and transportation contexts.

Decommissioning, as a complex project, requiring understanding of several critical activities, technical and organizational aspects and the links between them. Multidisciplinary collaboration is therefore required. The DISC model and TUKU questionnaire can be tailored to particular decommissioning phases and activities with safety culture assessment then contributing to the identification of decommissioning related organizational and sociotechnical challenges and opportunities.

3.4.1 Discussion

The regulatory strategy in this context means a coaching type of strategy whereby the regulator encourages the operator in a positive manner by asking questions that pave the way to improvements. The strategy for complex projects such as decommissioning, is therefore to have a process by which both the regulator and licence holder can develop common understanding and then develop necessary competencies in parallel.

3.5 First decommissioning experiences in Finland: VTT's FiR 1 TRIGA reactor and OK3 radioactive materials research laboratory

Markus Airila (VTT Technical Research Centre of Finland) presented.

In 2012, the decision was made to shut down the FIR 1 TRIGA reactor, and operations ceased in 2015. This will be the first nuclear facility to be decommissioned in Finland. In 2016, plans were developed for dismantling and a licence application for decommissioning was submitted in 2017. A public hearing then took place in 2018, STUK undertook a safety assessment in 2019 and a license to decommission is awaited. Dismantling, waste removal and clearance is planned to take place in 2022-2023. Currently, preparatory works are ongoing and Fortum, as the main contractor, is finalizing the detailed dismantling plan and instructions. The SNF was recently shipped to the US for re-use at another TRIGA research reactor. With this being the first decommissioning project in Finland, there have been many discussions with the regulators.

Radiation and nuclear activities are governed by two ministries in Finland (the Ministry of Economic Affairs and Employment and the Ministry of Social Affairs and Health). The Radiation and Nuclear Safety Authority (STUK) is responsible for regulating Licensees and users of radiation (including VTT).

The licence application is governed by the Nuclear Energy Act. The first stage in the application was technical planning and a range of background reports for the environmental impact assessment were developed. Dismantling planning followed this, which provided the technical basis for the licence application that was submitted to the government. Various supporting appendices and technical reports were also submitted to STUK. The licence application and supporting documents were submitted in 2017 (Figure 8).

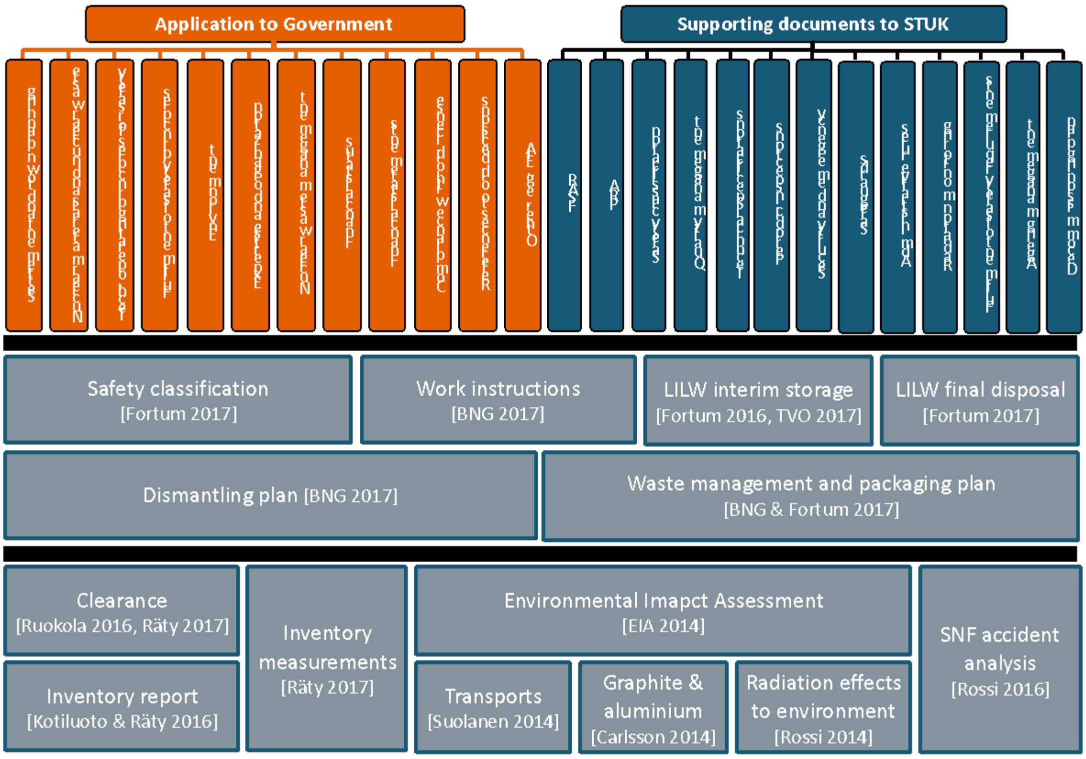

Figure 8 Content of the FiR 1 reactor decommissioning licence application and supporting documents.

An emergency preparedness and response exercise was undertaken for the reactor site. The accident scenario involved 24 fuel elements being dropped during a SNF handling, resulting in elevated external radiation levels and potential ground contamination. Analysis showed that shielding with a concrete wall and use of lead blankets put in place using an extender machine enabled the area to be made safe enough for recovery operations to take place. By taking such actions, dose levels could be reduced significantly such that it would be feasible to clean up the area and return to active operations.

Planning for decommissioning began in 2007 with a consultation on the various options to execute the project. Review of the decommissioning plan led to recommendations for improvement being received. In 2013 the environmental impact assessment phase took place, where, besides considering broadly all impacts of decommissioning, also different demolition and dismantling techniques were considered from a technical point of view. International experience was drawn upon from similar research reactors internationally. This fed into a more detailed dismantling plan that was developed in 2016 and that was specific to the FiR 1 reactor. This plan outlined the specification for dismantling works, was used as the basis for procurement and was the basis for the decommissioning plan that was submitted in 2017. The dismantling plan was further refined prior to dismantling activities to ensure all practical considerations were included, such as site logistics, waste acceptance criteria and integrated dismantling, waste management, radiation protection and security operations. A contract was made in 2020 with Fortum for the dismantling activities and waste management.

Throughout the different stages of planning, costs and timescales have changed considerably. In 2005, the main dismantling phase was estimated to take 3.5 months. This increased to between 12 and 16 months by 2018 and costs rose from an estimated 5 million Euros to between 20 and 30 million Euros to take account of possible SNF interim storage options at the NPP site to allow dismantling to commence.

The FiR 1 reactor will be the first nuclear facility to be decommissioned in Finland and there have been a number of lessons learned as the licensing process has progressed. The regulator, operator and ministries have all learned considerably during the process and Finnish laws have been updated to take account of experience gained. Much of the experience was gained by the operator as an ‘active owner’ in the project. As a result of experience gained in project organization, radiation protection and contamination prevention practices have been upgraded and, whilst operations personnel were retained to ensure knowledge retention, the workforce has been expanded to further the decommissioning experience of staff. A safety culture assessment was undertaken in 2018 and recommendations are being implemented.

The main challenge was the uncertainty over waste management solutions at the time of shutdown. Several years of negotiations were necessary to achieve a convergence of plans. Solutions have now been identified and the licence should soon be in place.

Further information is available from the following websites:

→ http://www.vttresearch.com/services/low-carbon-energy/nuclear-energy/decommissioning-of-finlands-first-nuclear-reactor

→ http://tem.fi/en/vtt-technical-research-centre-of-finland-ltd-s-licence-application-for-decommissioning

In addition to the FiR 1 reactor, a laboratory for radioactive materials research is under decommissioning. The laboratory was operated for a 40-year period from the 1970’s. The safety culture during operations was not of the current standard, resulting in various legacy problems, including the OK3 hot cell where irradiated metal samples were opened and processed. The hot cell contained a lot of radioactive waste, including dust, and had a gamma dose rate of 60 mSv/h. It was a large operation to clean up the cell and planning and implementation were conducted together with Fortum/Loviisa. It was a difficult working environment. Nonetheless, works were completed with a relatively low cumulative dose of 3.4 mSv and the resultant dose rate following dismantling of the cell was 0.02 mSv/h.

3.5.1 Discussion

Contractual issues relating to waste management were the key reason for decommissioning of the FiR 1 reactor taking so long from the initial decision to decommission being taken. It takes time for contracts to be put in place at nuclear sites and the time required for the procurement process was underestimated. Especially the transfer of nuclear liability and the financial liability on nuclear waste management were relatively challenging questions to resolve. Furthermore, there wasn't a national strategy for the management of radioactive waste in place and waste contracts had to be made on a commercial basis. Also, while the FiR 1 waste issues were solved between companies (VTT and Fortum), a national waste policy has now been developed which provides a good basis for moving forward in future cases. The policy integrates all radioactive wastes, not just those arising from nuclear sites.

3.6 Environmental Cumulative Risk Assessment – addressing radiation and multiple stressors for research and regulations

Knut Erik Tollefsen (Norwegian Institute for Water Research (NIVA)/CERAD, Norway) presented.

Predicting the risks from chemical mixtures and multiple stressors is a complex issue. There are a wide range of potential stressors, including toxic chemicals, ionizing radiation, solar radiation, biohazards and temperature differences that can interact. Those interactions may be additive, antagonistic or synergistic, which complicates how environmental and human health assessments can be approached since effects cannot just be summed.

NIVA has developed a concept called "Source to Outcome Pathway" as a platform for activities in NIVA's computational toxicology program, NCTP (www.niva.no/nctp) that links partitioning of emissions of pollutants within different parts of the environment, internal and external concentrations and, ultimately biological responses and adverse outcomes (Figure 9). The approach combines knowledge frameworks such as the aggregated exposure pathway (AEP) and adverse outcome pathway (AOP) into a holistic set of models that allow the prediction of impacts from different sources of exposure.

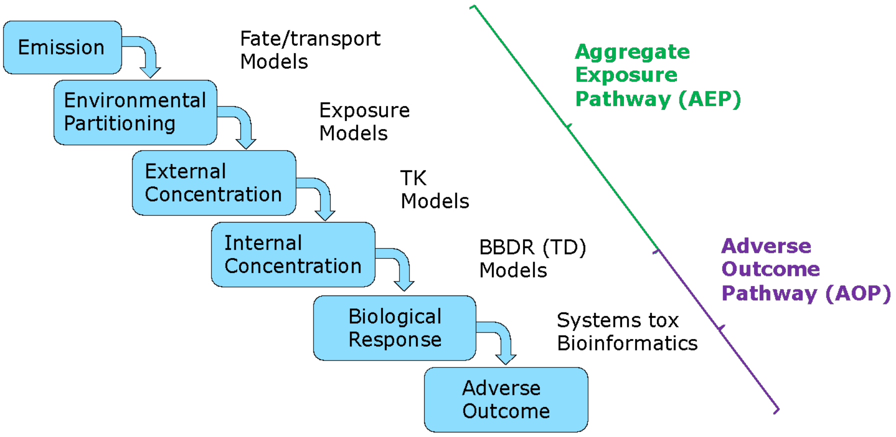

Figure 9 NCTP Source to Outcome Pathway (STOP) framework (from www.niva.no/nctp).

A cumulative risk assessment toolbox, the NIVA Risk Assessment database (NIVA RAdb) tool (www.niva.no/radb) has been developed to perform rapid and standardised predictions of risk, identify susceptible species and risk drivers, and characterise the most likely modes of action of complex mixtures of stressors (Fig. 10). The overall objective is to link exposure (i.e the AEP) to effects (i.e. the AOP), and use quantitative exposure data to predict exceedance of no-effect (environmentally safe) thresholds and enhance our mechanistic understanding of the risk risk single and multiple stressors represent. Such assessments are performed on basis of exposure data from environmental monitoring campaigns or from exposure predictions, and the outcome of the risk predictions can be used to characterise spatiotemporal patterns in risk. Experiments with chemical mixtures and multiple stressors are currently undertaken to validate these prediction models .

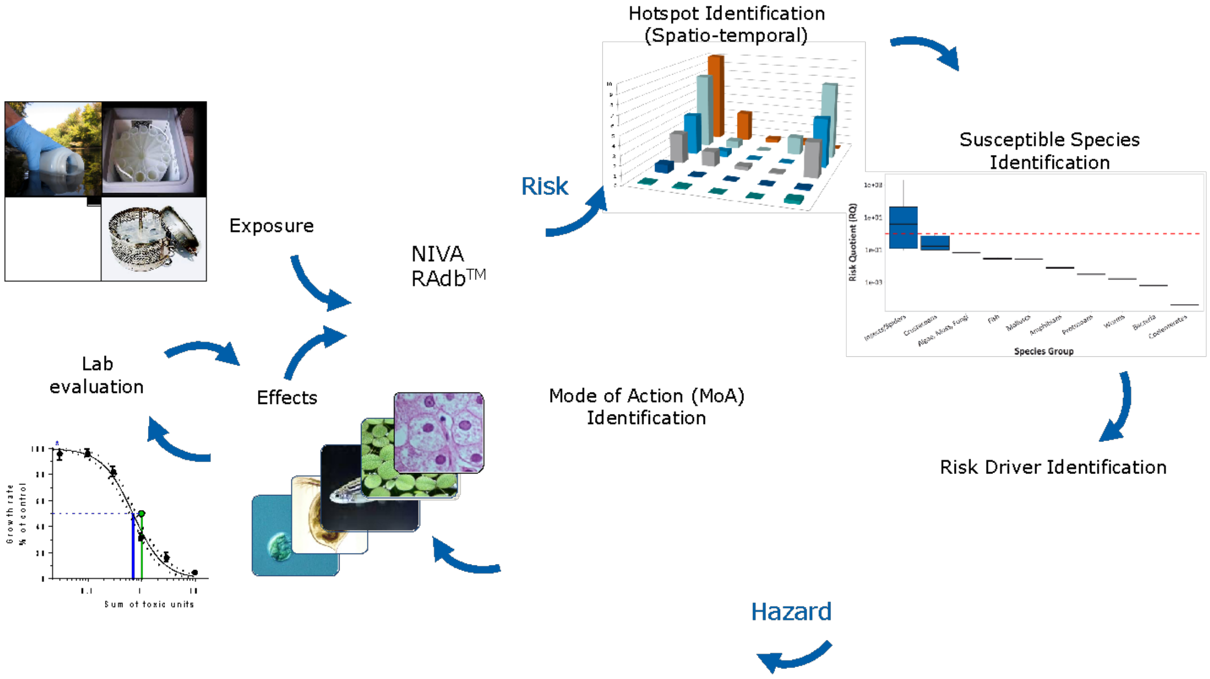

Figure 10 Analysis pipeline for evaluating modes of action and effects from exposure to stressors, assessing cumulative risk, and identifying risk drivers for different stressors (see www.niva.no/stop for details).

The approach has been applied in a simulation study at the Jarenvannet Lake in Norway. The case study involved a theoretical exposure simulation for a complex mixture of chemicals and radionuclides from waste materials, in addition to exposure to natural non-ionizing (UVA and UVB) and ionising radiation. Experimental data from controlled laboratory studies are preferably used, but complemented by quantitative structure-activity relationships (QSAR), when relevant. Risk hotspots were identified within spatial (geographical) and temporal (time) scales, and species groups being susceptible to the cumulative exposure identified by ranking according to the exceedance of risk thresholds. The risk predictions were undertaken both in light of short (acute) and long (chronic) exposures, and the stressors with the largest risk potential (i.e. risk drivers) identified to support mitigation activities. Whilst there is an implicit assumption of a cumulative contribution to risk, the cumulative risk is often restricted to contribution from a few stressors, which often seems associated with classical priority pollutants rather than radionuclides and/or different types of radiation. This is evidenced by a number of other case studies, including oil platform decommissioning and the use of Alum Shales in road construction for which classic pollutants such as metals were the main key risk contributors.

A graphical user interface (GUI) has recently been developed and implemented as a front-end visualization tool for the NIVA RAdb (see www.niva.no/stop) The GUI named “Source To Outcome Predictor (STOP)” supports display of data from NIVA RAdb in standardised ways, and assessment of specific locations, seasonality, species groups, exposure durations, effect types and risk prediction approaches. The tool boxes and GUI has only recently been developed and are currently being tested using a number of case studies. It is envisioned that the tools have the potential to aid risk management by considering retrospective and prospective risk assessments as well as assessment of mitigation measures. The approaches can also support data gap identification, development of new biological test systems (bioassays and test guidelines) and regulatory research.

4 Session 3: Challenges

Session 3 focused on the sharing of research conducted to reduce scientific uncertainties, including methods and results for improved waste characterization from a waste and materials end-state perspective and site characterization to support decisions on remediation and waste storage and disposal, and the identification of continuing challenges and the scope for them to be addressed through future research projects.

4.1 Site understanding as a foundation in radioactive waste disposal, legacy site and decommissioning programmes

A series of four presentations was given on the topic of site understanding as a foundation in radioactive waste disposal, legacy site and decommissioning programmes.

4.1.1 Site understanding strategy

Tobias Lindborg (Blackthorn Science, Sweden) presented.

Site understanding is the whole package dealing with the site and not just data for models. It includes understanding of how the site functions and how different features and processes are interlinked. It also includes descriptions, models and experts and their experience and knowledge and the possibility for them to transfer that knowledge to the next generation. A conceptual site model then draws on that site understanding. The conceptual model highlights the parts of the system to be assessed, gaps in knowledge and processes and linkages between parts of the system. If the installation in question and associated barriers are also incorporated then it becomes a total system conceptual model. A conceptual model represents a holistic way of thinking that helps optimize further planning and execution of the assessment method.

System understanding is a therefore central function in radioactive waste management programmes. It is based on scientific understanding and research and thus underpins safety assessments. The process begins with a clear definition of the project objectives, e.g. remediation of a site or disposal of some waste at a site and the system that is to be assessed, which is described in terms of the inventory, waste type and the biosphere and geosphere that constitute the natural system at the site in question. Evolution in time has to be understood to capture features, events and processes that need to be assessed. Together these are used in design, environmental impact assessments and safety assessments to develop a solution. It is an iterative process with feedback to system understanding at each stage in the programme in order to address knowledge and data gaps and inform the decision to progress to the net stage.

This understanding has been reflected in a recent project undertaken by Working Group 6 of IAEA MODARIA II on enhancement of the BIOMASS methodology. Thinking of system understanding as a central element to biosphere assessments in support of radioactive waste management has arisen not as a result of a single national programme, but as a result of international programmes that have highlighted the need for increased focus on system understanding and continued iteration between different programme steps. As such, the overall safety case as well as the assessment context continually develop throughout the radioactive waste management programme, being updated as system understanding increases. The development of system understanding requires an interdisciplinary approach that links a range of scientific disciplines including geology, hydrogeology, biogeochemistry, ecology etc. Developing understanding of the history of a site and its evolution to current conditions is also an important element, providing the basis for describing possible future developments of the site in terms relevant to preparation of a safety case.

Definition of a site for assessment purposes is a necessary first step, even if the programme is at a site-generic stage, since assumptions about the nature and features of the site will be required. A holistic approach to characterization of sites is needed that integrates different disciplines.

There have been numerous developments made nationally in radioactive waste management programmes and in international forums such as the IAEA and BIOPROTA. These developments need to be harmonized in an overall methodology that enables safety to be demonstrated, irrespective of the type of programme. It is important to recognize that there are dependencies between different parts of the system when approaching assessments and site characterization programmes. The development of system understanding as a central platform to safety assessments facilitates a graded approach and supports optimization.

4.1.2 Integrated hydrological site understanding

Emma Lindborg (DHI, Sweden) presented.

Water is the main driver for element transport between different systems. There is a complex integrated system between groundwater (saturated and unsaturated flow), surface water and the atmosphere with many different interactions that need to be taken into account, including between shallow and deeper groundwater. Such a joined-up system approach is needed when following a radionuclide or other contaminant from its source to whichever part of the environment the impact could occur, allowing for analysis of geochemical and other interactions along its flow path.

It is important to include hydrological characterization of a site at an early stage of the site selection/evaluation process in order to identify the possible discharge locations in the surface environments and inform the dose modelling strategy. Such characterization provides information about the hydrological properties to be taken into account in dose calculations and helps inform on how the biosphere may develop under different future climate evolution scenarios.

A coupled groundwater-surface water model makes it possible to analyze a range of highly relevant questions, including how water is flowing in space and time today, how much, if any, dilution occurs at the surface and the quantification of the groundwater flow paths and travel times from those facilities to places where impacts occur. A coupled model also allows recharge and discharge areas to be mapped and the influence of climate and landscape changes on catchment hydrology to be analyzed. If evapotranspiration processes are incorporated, the quantification of plant root uptake of contaminants transported in water can be evaluated.

Hydrological understanding can support planning for the collection of baseline monitoring data. For the planning of site investigations and monitoring, early-stage modelling and characterization can support cost effective planning of site activities and optimization of the location and number of measuring points. Thereafter, learning at each iteration of a staged programme is also extremely important, particularly when moving from generic to site-specific models and data.

It is important for hydrology/hydrogeology to be integrated with other disciplines in order to get hydrological simulations right. For example, the type of vegetation present and land use, ground surface geometries, regolith and stratigraphy and bedrock properties will all affect hydrology.

DHI has a toolbox for integrated hydrological-hydrogeological modelling, consisting of a set of tools that can be used to answer questions relating to water-driven contaminant transport in different parts of an integrated surface-bedrock system (Figure 11). The different models can be linked to address particular questions and account for greater complexity as site understanding develops within an iterative approach.

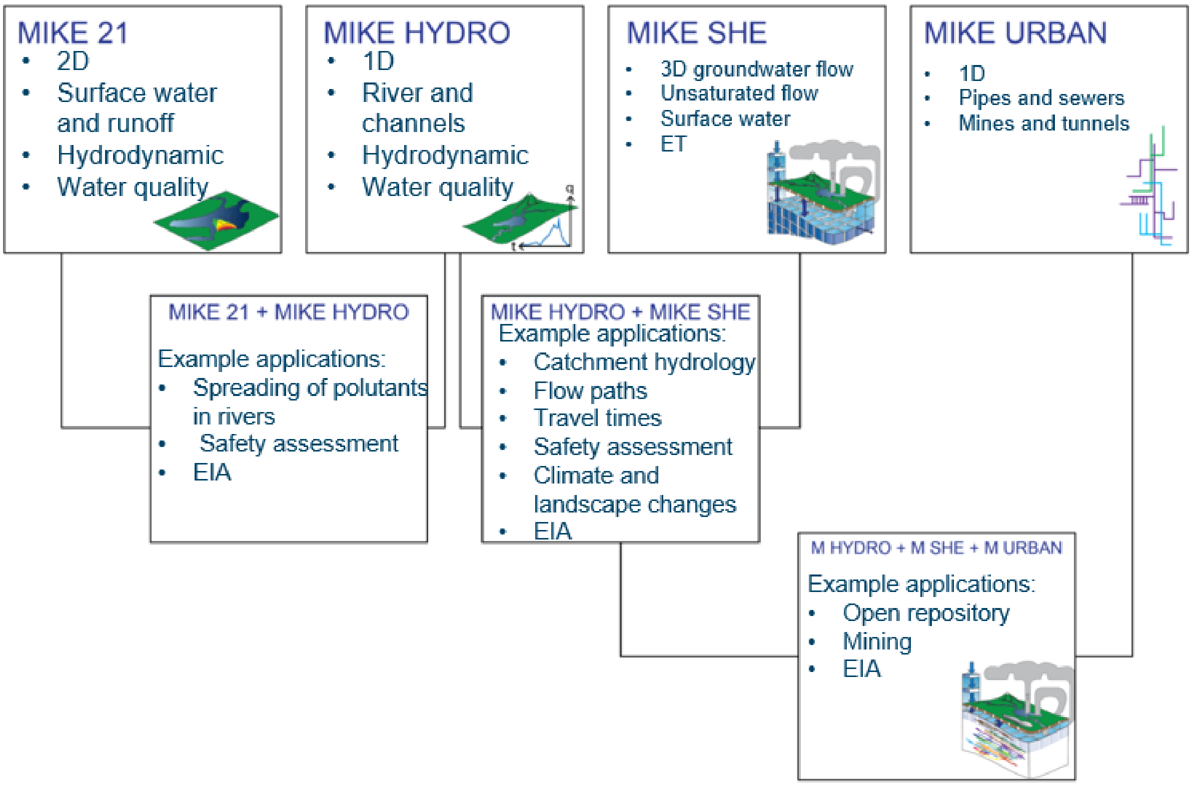

Figure 11 DHI toolbox for integrated hydrological-hydrogeological modelling.

4.1.3 The Greenland Analogue Project

Lillemor Claesson Liljedahl (DHI, Sweden) presented.

Deep geological repositories use a multi-barrier principle aimed at isolating waste from the surface environment over long timescales (up to 1 million years). Over this, time scale glacial conditions are expected to reoccur in regions that were previously glaciated. These climate-induced changes (i.e. the advance and retreat of ice sheets and development of permafrost) will influence and alter the surface and sub-surface environments and have the potential to impact repository performance. Observations from sites with existing ice sheets can help reduce uncertainties and provide a stronger scientific basis for the treatment of glaciation within safety assessments through improved process understanding.

There are a number of glacial processes that may impact the long-term facility performance of a repository facility and the engineered barriers. The meltwater produced during ice sheet melting contains high amounts of dissolved oxygen which, if it penetrates the geosphere to large depths, can corrode copper canisters. The meltwater is also typically very dilute, which may impact the buffer stability. As ice sheets advance and retreat, surface erosion occurs. During retreat, mechanical unloading can result in earthquakes that have the potential to cause canister failures. During the glacial maximum, ice sheets of 2 and 4 km thickness may be present, which will affect the pressure regime at depth. This high-pressure situation has the potential to affect canister integrity. During a glacial cycle the permafrost depth will vary, and knowledge of permafrost evolution over time is of relevance since permafrost may affect the integrity of the repository facility.

In 2008, SKB began the Greenland analogue project (GAP) in collaboration with the Canadian Nuclear Waste Management Organization (NWMO) and Posiva in Finland. The project was aimed at addressing knowledge gaps with regard to the influence of glaciation processes on the safety of geological repositories, with Greenland being selected as the suitable analogue study site. The Greenland ice sheet is similar in size to ice sheets known to have existed in the past across Fennoscandia. The crystalline bedrock also shares similarities with the bedrock in Fennoscandia and Canada. The Greenland ice sheet is also relatively accessible compared to the Antarctic ice sheet. The Greenland ice sheet therefore provided a very useful natural analogue to study glaciation processes expected to reoccur over the safety-relevant timeframes for a deep geological repository.

To achieve the required improved process understanding, research focused on obtaining information contributing to answering a suite of project questions, including:

- Where is meltwater generated under an ice sheet?
- To what depth does glacial meltwater penetrate into the bedrock?
- What is the chemical composition of glacial water if and when it reaches repository depth?
- How much oxygenated water will reach repository depth?
- What is the hydraulic pressure situation under the ice sheet driving groundwater flow?
- Does the discharge of deep groundwater occur in taliks below lakes?

These questions formed the basis for planning and designing the site investigations and site modelling.

Field studies carried out on the ice sheet were made to inform understanding of ice sheet hydrology and groundwater dynamics and included both direct and indirect observations. Indirect observations were used to study the basal system and the understanding of which parts of the ice sheet contribute to groundwater infiltration. Direct observations of thermal and hydrological conditions at the base of the ice sheet were possible as a result of hot water ice drilling. Geosphere investigations were also undertaken to study groundwater flow dynamics, composition of groundwater at depth, the extent of permafrost, redox conditions and the infiltration of glacial meltwater to bedrock. Three deep bedrock boreholes were drilled through the permafrost and subsequently instrumented to facilitate hydraulic testing and hydrogeological/hydrogeochemical monitoring. Such investigations were paired with geological mapping, water type characterization, thermal studies and geophysical investigations.

As a result of the field investigations, it has been possible for the first time to describe where and how groundwater is formed under an ice sheet, how water pressure under an ice sheet varies in time and space, and how an ice sheet influences the groundwater flow, all of which are relevant to groundwater models. It has also been possible to describe how deep meltwater can penetrate the bedrock and the chemical composition of this water, which is of relevance bentonite buffer stability and canister corrosion. The output thereby helps to ensure that assumptions in safety assessments are realistic and have been useful in addressing regulatory questions.

As a result of the GAP, 21 technical reports and over 60 scientific publications have been produced with the output being used in ongoing safety assessment modelling work at each of the GAP organizations. The two final GAP reports are SKB Reports R-14-13 and TR-14-13, providing the final data and description of gained process understanding (Harper et al. 2016; Claesson Liljedahl et al, 2016). The GAP project is now ended, but SKB is continuing monitoring at the site, and further process-specific field studies are possible to be undertaken at the GAP site.

4.1.4 Using mass-balance models to understand the biogeochemical cycling of elements

Johan Rydberg (Umeå University, Sweden) presented.

The Greenland Analogue Surface Project (GRASP) was conducted as a sister project to the GAP. SKB is also currently collaborating within the Catchment Transport and Cryo Hydrology Network (CatchNet), along with NWMO (Canada), COVRA (Netherlands) and NDA (UK). CatchNet aims to increase understanding on periglacial and glacial systems and how they affect water and element transfer through the landscape.

Where there is a system of interest, models can be developed that consider the flow of water and elements throughout that system. However, with changes in climate, the representation of water and element flows will vary. Natural analogues can be used to inform on how such changes may affect flows. For example, studying a similar system in a warmer, wetter climate can provide data that can then be applied in the models to help represent water and element flows at the site under similar warmer and wetter climate conditions in the future. Care is needed to assure the transferability of data and models from one site to another site. For example, in moving from a from a boreal landscape to a cold dry environment, precipitation will decrease, which will reduce the export of elements. This can be readily represented in the model by downscaling precipitation and lowering element export. However, if you go to a system and measure that element export parameter, higher values than those in the model may be observed since other important processes associated with that system have not been taken into consideration, such as increased input of aeolian material. It is therefore important to ensure that, in transferring a model from one system to another, it is adjusted to the new site conditions. Consideration needs to be given to the differences between systems, rather than just scaling parameters. Site specific knowledge is therefore required for both the actual site and the analogue site through site characterization.

The Greenland Two-boat lake catchment provides an example. The catchment is associated primarily with sand-silt soils and there is very little water in the system – there are no permanent streams, but glacier meltwater is present at certain times of the year. The catchment has been well studied and a lot of hydrological modelling has been undertaken. This modelling has provided input for a mass-balance model for the system (Figure 12).

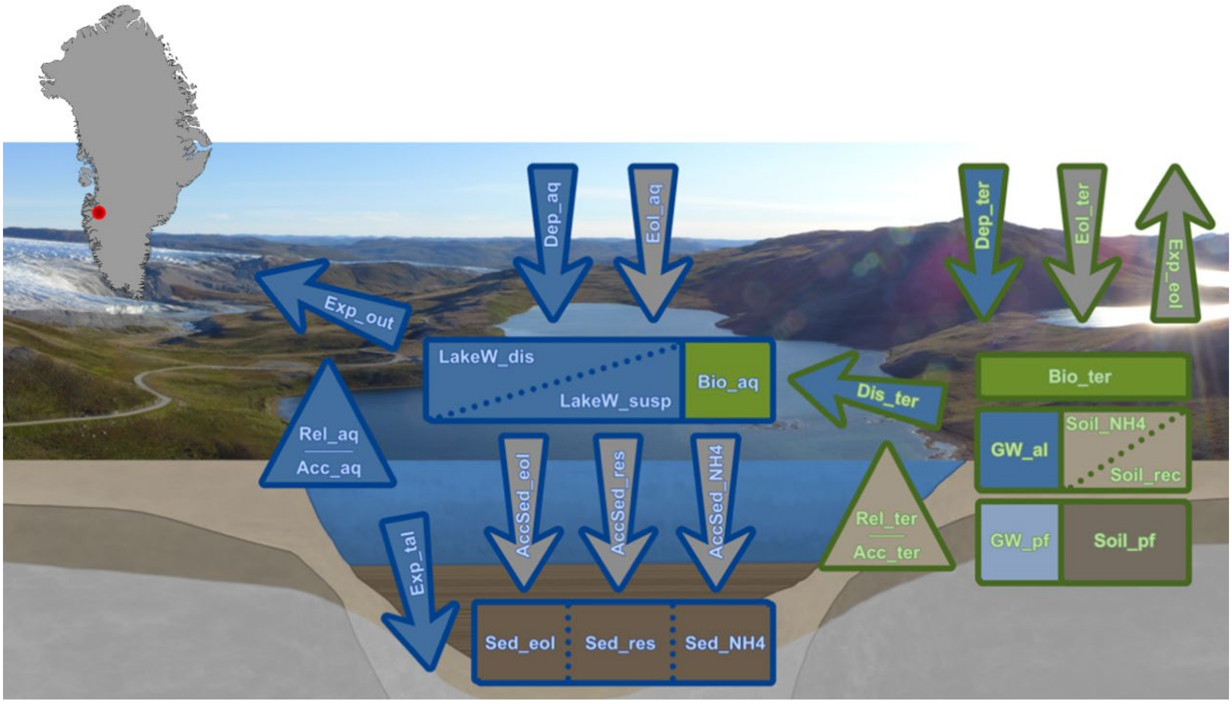

Figure 12 The Two-boat lake mass-balance model.

Under current conditions, lithogenic elements such as zirconium are bound to particles and, as such, move in particulate form through the system. There is a large input of such elements from aeolian deposition to both terrestrial and aquatic areas of the catchment with lake sediments and terrestrial soils being sinks for these inputs. If warmer and wetter climate conditions occurred, with permafrost and ice being removed from the system, aeolian deposition would be removed and precipitation would increase, giving rise to streams and the fluvial transport of particles and terrestrial sediments turn from sinks to sources. Whilst lake sediments remain a sink, the concentrations are reduced.

In the case of halogens (e.g. iodine and chlorine), these are in dissolved form. Under current conditions, wet deposition is their main pathway into the catchment where they remain mostly in the aqueous phase in lakes although there is some retention in sediments. Accumulation in terrestrial soils also occurs due to their binding to organic matter and the limited opportunity for washing out due to the brief melt season. Evaporation leads to increased concentrations in the lake. However, under a warmer and wetter climate there would be increased deposition to both terrestrial and lake parts of the catchment. The increased precipitation could, however, turn soils from a sink to a source as a result of increased soil erosion. The increased flow of water in the system would also lead to increased exports from the system as a result of downstream transportation such that lake water concentrations would be reduced.

4.1.5 Discussion

In dealing with climate change over long timescales, climate experts describe possible future scenarios and snapshots in time are selected where different conditions may exist, such as permafrost rather than considering the evolution to and from different climate conditions. SKB report TR-19-09 summarizes the latest understanding from recent climate work for Swedish sites. In addition to climate, topography will also change over time. How climate has been treated by SKB in safety assessments is also reported in SKB report TR-20-12.[6]

In order to map fracture systems and bedrock properties, boreholes were drilled from which hydrological testing was possible. A large number of investigations took place in order to describe and map the bedrock geology.

Greenland was a good analogue site for Sweden, but its suitability to other countries, such as Norway will vary depending on the geological conditions. Topography will also differ, which may be an important consideration. Knowledge on future climate stages can, however, be coordinated across the Nordic countries. A particular challenge for Norway is that there is a poor background monitoring network (NVE) as compared with Sweden. In particular, data to quantify recharge and discharge in fractured bedrock systems are lacking.

4.2 EMRP and EMPIR decommissioning projects

Simon Jerome (CERAD, Norway) presented.

The EMRP and EMPIR decommissioning projects, on risk assessment and safety assessment supporting regulatory supervision of decommissioning and waste management for nuclear research and radiation facilities, are being run under the European Association of National Metrology Institutes (EURAMET). The projects aim to improve the quality of measurement infrastructure, support radioactive waste disposal and benefit society.

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[6] The SKB reports are available athttps://www.skb.com/publications/

MetroRWM (metrology for radioactive waste management) began in 2011 and ran until 2014. It was focused on developing standardized and traceable measurement technologies for gaseous effluents and the development of measurement standards. This was extended through MetroDECOM (metrology for decommissioning nuclear facilities) to the development of methods for characterization and the development of reference materials and calibration standards. MetroDECOM II then built upon the previous projects to further develop measurement systems for on-site measurements. There were a number of common themes throughout these projects, including the development and realization of free-release measurement systems and development of remote contamination mapping technologies.

A free-release measurement system was developed by the Czech Metrology Institute and installed at a site in Spain. The system is readily transportable, using concrete rather than lead which is toxic, and germanium detectors that are more accurate than neutron detectors. Evaluation software has been developed and supports the installation. The system has been calibrated for various boxes, bags etc. containing mixed materials, including contaminated pipework.

A waste characterization system has also been developed. This is an automated drum measurement system where drums are weighed, and dose measurements made on contact and at a distance of 1 m. The system helps in understanding the distribution of radioactivity within the drum.

One of the most innovative developments is an off-gas in-situ monitoring system for the measurement of carbon-14 (C-14) that uses spectroscopy to measure quantities in the atmosphere. The technique compares absorption lines from stable carbon dioxide (CO_2) with $^{14}CO_2$. It is capable of measuring concentrations as low as 2 Bq/m^3 $^{14}CO_2$. It is also capable of differentiating between C-14 labelled CO_2 and methane (CH_4).

Remote monitoring systems that have been developed as part of the projects can be deployed prior to demolition of facilities to allow dose mapping. Techniques are available that monitor alpha radiation and gamma contamination.

The projects have resulted in improved measurement quality for difficult to measure radionuclides that will, as a result, lead to improved models for workers and members of the public. The measurement systems can be deployed more efficiently than previous systems and will help ensure a more efficient use of waste repositories through more accurate waste characterization to ensure appropriate wastes are consigned to appropriate repositories or free released. This is vital for accelerated decommissioning programmes and can lead to significant cost reduction for decommissioning.

4.3 Stakeholder engagement to support decommissioning and waste management

Deborah Oughton and Yevgeniya Tomkiv (CERAD, Norway) presented.

Mistakes can be made in stakeholder engagement. For example, in early examples of stakeholder engagement, the practice was seen as bureaucracy that had no real impact on decision making. In another example, whilst people were engaged, insufficient time was allocated to discussing the broader framing of the issues; the stakeholder group wanted to discuss whether waste should be produced in the first place rather than focusing on the solution to the waste and this led to frustration. Allowing people to discuss the broader issues can lead to greater engagement at later stages of the process. Expert dialogue is also needed as input to discussions and often this is lacking. The arrangers may also be viewed as lacking independence, leading to suspicion and skepticism or the timing may be wrong – the process should be continuous and appropriate to the stage. There is also the risk that too much weight can be placed on public opinion with the public being blamed for their perceptions. Stakeholder fatigue should also be avoided.

From a social science viewpoint, it is possible to explain why mistakes happen. One typical problem in stakeholder involvement is that societal aspects are not taken into account to the same extent as other aspects so there is discussion around costs, technology, safety and the environment, but social impacts are either missed altogether or are considered at a late stage.

There are different views as to what constitutes risk communication. Historically, approaches leaned toward what is termed the technical ideal whereby experts inform and persuade the public on the results of risk analysis and the decisions of risk managers, the objective being to inform, persuade and influence behavior. At the other end of the spectrum is the democratic ideal which is a rule-governed process where all parties affected by risk are guaranteed maximum participation and power in decisions, with the objective of reaching mutual understanding and informed behavior.

Another reason behind past failures in stakeholder communication is how the motivations for public and stakeholder participation have been framed. Often the focus is on securing the endpoint, so decisions have already been made and stakeholders have no opportunity to influence the outcome rather than accepting that participation is, in fact, part of the decision-making process. More engaging motivations would be “to achieve better solutions” or “because it {involvement} is the right thing to do”.

A number of criteria have been discussed in social sciences by different scholars in order to consider how to approach engagement, respect democratic ideals and avoid mistakes from the past. This includes ensuring inclusivity so that all with relevant expertise are involved, including those who are usually excluded, to open up discussions which, in turn, will help in achieving better decisions. The process should be continuous and flexible, building on previous activities and allowing new issues to be taken into account. Discussions also need to be allowed to have a genuine influence on the final decision and there should be independence around decisions on who is invited to participate to avoid exclusion and bias in the actors responsible for decisions. It is also important to be transparent as to how the engagement process is being conducted, but also as to the purpose, aims and who benefits from the process. Engagement is not about educating, but rather mutual learning for all participants, including the organizers and sponsors, and there should be accountability such that all concerns and issues raised are recorded and responded to. The process should be approached with open minds and a willingness to learn from one another.

There is a lot to be learned from past practices and theoretical developments in the field. Being critical of what has been done in the past and learning from experience will help support a change in thinking and improvement in the stakeholder engagement process. The importance of societal aspects needs to be recognized and participation embraced as a norm in the decision-making process.

It is important to build on learning from mistakes, but also from success stories, evaluating what has and hasn’t worked well. Risk perception can be an issue and should be taken into consideration through, for example, comparison of different risks and stressors to help place issues into perspective. Sustainability challenges can also be an issue with trying to find a balance between development goals and environmental and societal concerns.

When beginning an engagement process, consideration should be given to the appropriate starting point, recognizing there may be different stages of engagement as projects progress. It should also be recognized that there will be a range of things that need to be discussed, including how to go about making decisions and roles for the various stakeholders should be clarified. More concrete case studies can be useful in helping to identify what more is needed in terms of the stakeholder engagement process and to identify further research needs.

4.3.1 Discussion

An occasional omission in stakeholder engagement is to forget where successes have been achieved. Good practice guidance on the application of sustainable practices to the management of decommissioning wastes from nuclear licensed sites was developed through a learning network comprising groups with very opposing views. Nonetheless, progress was made with the different groups agreeing on a set of working principles around how stakeholder engagement processes should work. The documentation and related guidance are available from www.safegrounds.com/archive.htm.

Experience gained from legacy site management has demonstrated that the involvement of affected stakeholders is crucial and results in a much more effective process.

5 Discussion Group Feedback

Workshop participants were divided into four working groups to discuss the following questions:

- → What are the key contaminants (radionuclides and chemicals) from research facility decommissioning and what makes them key?
- → What environmental media exposure pathways are important for these key contaminants?
- → What site characterization data are important?
- → Are the answers different for operations and for releases in the future (e.g. from repositories)?

In addition to discussion of these questions, a number of additional discussion topics resulted from the working group sessions. Collective feedback from the working groups is summarized below.

5.1 Key contaminants from research facility decommissioning

The key contaminants for any facility vary according to the inventory. Typically, for research reactors and other research facilities, the radioactive waste inventories are not well known and can include diverse components with unusual features linked to unique features of particular research programmes. The proportions of fission and activation products will depend on the particular research and other[7] activities carried out and the reactor design and the mode of operation. Written records and personal memories can help in developing an understanding of the inventory, but this may not be sufficient in itself to progress decommissioning planning and activities. It was noted that some radionuclides that may have significant long-term impacts may not be present today but will arise later due to ingrowth.

Key radioactive contaminants are diverse and can include:

- → Activation products: Co-60, Ca-41, Ni-59, Mo-93 etc.
- → Fission products such as: Cs-137, Kr-85, Sr-90, Cd-113m, Sn-121m, Sm-151, Eu-155, Se-79, Zr-93, Tc-99, Pd-107, Sn-126,
I-129.
- → Fuel activation products such as: Am-241 and isotopes of uranium, neptunium, plutonium and curium isotopes.
- → From non-reactor facilities: H-3, C-14, Cl-36.

Shorter lived radionuclides, such as I-131, that are often of significance in accident situations, tend not to be an issue for decommissioning because of the delay between the end of operations and the start of decommissioning work. Key radionuclides during current operations may not be the same as those that are important in the longer-term, e.g. in the period after emplacement of waste in a radioactive waste repository. For example, the current focus for research reactors in Norway is on Co-60 as an indicator of activity for occupational exposure during the handling of wastes. However, as the programme moves into decommissioning and disposal, a different set of longer-lived radionuclides will be important and a different characterization strategy will be needed, for example, because many of these longer-lived radionuclides are difficult to measure (NEA, in press). However, it may be appropriate to consider both aspects within one characterization programme, rather than handle the waste twice.

What makes a radionuclide 'key' is a significant contribution to radiological risk. The amount is obviously relevant but this may not be the dominant factor. Half-life and mobility are likely also to be important. Another challenge is that some of them, are difficult to measure. Scaling factors are often used to help quantify difficult-to-measure radionuclides for commercial reactors, but those may not be directly

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[7] Such as production of radiopharmaceuticals.

applicable to research reactors due to the considerable differences between facilities and operations. Some radionuclides, such as C-14, Ni-59, Ca-41, Mo-93 and Eu-155 are difficult to measure and have not been well studied such that information on their behavior (e.g. environmental transport) is limited.

In addition to characterizing the radioactive inventory, the chemical inventory should also be understood. Of the non-radiological contaminants, asbestos is one of the most challenging to deal with, but others, such as lead, cadmium and organic substances have also been identified. The chemotoxicity is also important in some cases. In the UK, for example, toxic heavy metals such as lead and solvents have in some cases been shown to be the limiting factor for site clearance.

The key chemical contaminants are diverse and, like radionuclides, tend to be site dependent. They may be hazardous themselves, such as asbestos, or may influence the behavior of radionuclides and thus affect the management and disposal of wastes. For example, complexing agents, such as EDTA and solvents used in decontamination processes, can increase the mobility of radionuclides, thus reducing the containment capacity of disposal systems. Chemicals used in solvent extraction, ion exchange resins and material generated from the decomposition of organic matter can also be problematic.

A further issue for research reactors is lack of knowledge of the aggregate composition used in the concrete bioshield, without which the inventory associated with neutron activation of the concrete is difficult to access.

Overall, it is considered worthwhile to maintain a broad view, particularly in early stages of a programme, and to avoid ruling out consideration of specific contaminants unless there are very clear reasons to do so. A holistic approach is suggested, taking account of radionuclides and other potentially harmful substances. General lists of key contaminants are available but should be used with caution. Consideration should be given to whether contaminants are applicable to each case.

The waste forms, dissolution properties and chemical properties, for both radionuclides and chemicals, are all important. This information, used alongside site characterization data, will support understanding of the potential for migration and accumulation of contaminants and the implications for exposure.

Consideration should be given to the availability of storage and disposal sites and the routing of different wastes, recognizing that different concepts may be required for the different types of waste. For some wastes, such as resins, there may be issues around finding disposal sites that can accept those wastes. Where different repository concepts are required for the different waste streams (e.g. geological disposal, near-surface, landfill), whether or not these facilities are co-located may be an important factor, particularly during planning stages.

5.2 Environmental media exposure pathways

The relevant exposure pathways will depend on a variety of factors, including site characteristics, time since shutdown, decommissioning plans, the formulation of particular regulatory and other protection objectives, and the timescale over which they are applied. The assessment endpoints of protection will also affect the exposure pathways of interest, with the pathways of concern potentially being different for the protection of people and the environment. For the protection of people, common immediate exposure pathways on site are release of contaminants to air and exposure of workers. In the longer term the focus is on members of the public and their exposure via air, water, ground and through the food chain. Radionuclide migration may be significantly due to transport in water, but other media and processes should not be neglected. For example, gases such as tritium, C-14 labelled gases and other volatiles can be transported in air. Particulates can also be airborne. There can also be aqueous run off from sites. In some cases, the focus may be more on the transport of contaminants to, and retention in, natural or seminatural environments. Many radionuclides of interest do not occur in nature, but stable element analysis can provide much of the data needed for assessments, particularly for long-lived radionuclides. It is noted that release, pathway and exposure scenarios may be different for safety and security assessments.

The characteristics and behavior of contaminants in the environment can also affect exposure pathways. For example, redox sensitive contaminants will be affected by the environmental redox conditions, which can lead to retention in certain environments such as mires and wetlands. A subsequent change in conditions, for example, drainage of a mire, may then lead to the release of previously retained contaminants. Changes in pH can similarly affect the mobility of contaminants. Microbial action can also be important. For example, the presence of methanotrophic bacteria can convert C-14 labelled methane to carbon dioxide that can then be incorporated into the food chain by primary producers.

Biogeochemical analysis may be useful in identifying the contaminants of interest and their relevant exposure pathways. For example, sorption properties can help identify those contaminants that are likely to be retained in the geosphere and those that could migrate to the surface environment. Sorption properties will similarly inform on the potential for contaminants to be transported through different environmental media and accumulated in yet others which, in turn, will inform the selection of relevant exposure pathways. Again, a holistic approach is recommended, taking account of the source, release and migration, and ensuring all aspects of relevance for exposure analysis are identified.

5.3 Site characterization data

Experience has shown that a first step in planning a site characterization programme is to first try to understand and describe the system in full, ensuring nothing is missed, and then consider what needs to be researched further. Interaction matrices and lists of features, events and processes can be useful[8], particularly when considering whether anything has been missed. Stakeholder involvement in the design of site characterization programmes can also be very useful to identify particular concerns or habits that should be captured in programmes. The needs of different end users of the data should be taken into account to ensure that the programme provides the necessary knowledge and data for different aspects of the programme (e.g. environmental impact analysis and operational and post-closure safety assessments etc.).

Characterisation is not just a pre-operational activity. Further characterisation needs will arise during operation and in decommissioning and/or in longer-term site management. A staged approach to characterization is therefore needed. For example, for waste disposal facilities, some characterization will occur prior to any construction (e.g. to establish a baseline) and some will be after (e.g. to take account of altered properties as a result of construction activities). Similar considerations apply in the case of in-situ disposal. It may also be appropriate to consider archiving samples for later analysis, in recognition of the long timescales of relevance for waste disposal. Characterisation to support safety in operation is likely to include relatively short-lived radionuclides, whereas for waste disposal, longer-lived radionuclides are likely to be of greater interest.

Site characterization programmes are not just focused on contaminants. Water and soil chemistry, geology, ecology, exposure pathways and the local population are all important aspects. The operational history of a site, including history of releases and discharges to the environment are also important considerations. In the case of disposal facilities, surface and bedrock mapping, fracturing and rock type are important considerations, including a significant focus on geological and geophysical investigations at a site. Surface and sub-surface hydrogeology may need to be studied, along with the interactions between them. In the case of radioactive waste repositories, for which the protection objectives extend for

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[8] For further discussion of the use of these concepts, see IAEA (2003). This work has been reviewed and enhanced in the IAEA MODARIA II programme and a report is due to be published.

thousands of years, understanding of climate change and how glaciation could affect a site may also be required.

A further aspect of characterization is the current and planned future use of land, and populations of humans and other biota.

It can be useful to consider and learn from examples and frameworks from other situations and other countries. For example, looking at the site characterization programmes undertaken in Finland and Sweden for repositories for various types of radioactive waste to identify key data needs etc., but also to learn from knowledge and experience of the techniques and processes for collecting that data, such as methods of sample collection and storage, or engagement with stakeholders. Learning from different programmes could provide the basis for the development of a general framework for characterization that could be applied to different sites and situations. The framework would need to be flexible enough for it to be adapted to the different contexts and specific sites, and also to take account of particular concerns and relevant interests of stakeholders.

5.4 Operational versus long-term releases

The differences between operational and long-term releases will depend on the site and future operations, the intended end state of the site and the programme for management of radioactive and other waste. There will be overlap, however, so knowledge acquired during operations can be used to inform decisions on future actions. However, decommissioning and waste management programmes progress over long timescales so there is a risk that knowledge may be lost over time (e.g. as a result of staff turnover). It is recommended, therefore, that plans and processes are in place to guard against loss of knowledge.

Dialogue with affected stakeholders is important, particularly in early stages of decommissioning and waste management programmes, in order to gain societal acceptance and identify particular concerns and interest areas. Local stakeholders are likely to be most affected in the early stages of programmes (e.g. as a result of construction activities) and the focus of their interest will be on the factors that affect them directly rather than particular features of a site that affect long-term safety. Enhanced engagement with local stakeholders around those stages of programmes with direct effects can therefore be beneficial.

It may be necessary for regulations and/or license conditions to be revised and new regulatory guidance issued to address different challenges faced through the stages of decommissioning and waste management as compared to operational challenges. It may be necessary to hold new emergency preparedness and response exercises related to different decommissioning stages to account for changes to access routes etc. and to test new accident scenarios, including around transport arrangements. Monitoring arrangements may also be different.

5.5 Additional discussion points

5.5.1 Adopting a holistic, proportionate and iterative approach

Holistic, proportionate and iterative approaches were discussed and considered useful concepts and worth further development. It is not possible to fully integrate everything from the outset, but this should not prevent progress. Where the only way forward relies on assumptions, these should be cautious and noted, so that their validity can be confirmed later, for example, by further research.

There are examples worldwide where decisions have not been made and progress has been delayed that has, in turn, resulted in a legacy that is more costly to remedy than would have been the case if dealt with at the time. At the same time, at many sites there has been significant learned experience and progress with risk reduction and wider aspects of remediation, including the application of interim end states. There is a difficult balance between acting too soon with decisions based on inadequate information and acting too late so that the situation degrades seriously in the meantime.

One approach suggested was to consider the minimum information requirements to support decisions at each stage, what scientific underpinning is needed to support that, and what would be the consequences of not obtaining that information. It is also important to ensure that all hazards are identified (radiological, chemical, physical) and for those hazards to be ranked proportionately according to the risks they pose so that priority can be given to addressing the greatest risks, and ensuring that solving one type of risk does not create another. Developing methods for managing the integration of all hazards and risks is, however, one of the major challenges.

The word 'holistic' can be used in different contexts and with different meanings. Its use should, therefore, be made clear when saying that a holistic approach is being adopted. Adoption of a holistic approach could mean that there is integrated planning to take account of all exposure routes, linked to the various risks and hazards related to safety and security and that different stages of a programme. It could also be holistic in terms of engagement with all relevant stakeholders as well as coordination between the operators of decommissioning facilities and waste disposal facilities.

It is important when planning decommissioning to take into account the final end state since this will inform on what activities are required and whether any wastes can potentially be left in situ. Stakeholders have a role in the selection of final end states, but it should be recognized that opinions can change so there should be flexibility. Nonetheless, some idea around the final end state is necessary to allow a route map to be developed, but this should not be prescriptive, at least in the early stages. It should allow for changes in opinion as well as scope to take account of new information. Such an approach is supported by defining the information needed to take the next step (discussed above). Support the information needed to make a decision to progress to the next step is defined, then that information is obtained, and the decision is taken. The basis for the decision can be made clear and transparent. However, if that information subsequently changes, or new information arises that challenges the decision, then a transparent basis for a change in plan or for continuing with a plan that is safe but no longer optimal on the basis of current understanding is available. As programmes progress, end state options can then be narrowed down and targets made progressively more detailed.

5.5.2 Regulatory framework

The process of satisfying regulatory requirements can be complex, given potentially conflicting requirements between regulations for radioactive contaminants and regulations for other hazardous contaminants, or the needs of safety in operations and safety in the long term. In some instances, the regulatory system may challenge the ability to progress with the optimum solution. In addition, there may be insufficient regulations to capture all the protection objectives and unplanned for situations faced during decommissioning and legacy management. Discussion may be useful, to determine whether specific regulations might be needed to address specific circumstances at a given site. Input from the scientific community may be a part of that process, in terms of improved characterization of the situation and assessment of the impacts of alternative ways forward.

Several of the presentations have noted that the regulations and guidance will in many cases need to be modified when they are first applied to a real legacy situation. A rigid/fixed set of regulations/guidance will only work well when it is being applied to a standard well-defined problem.

5.5.3 Site selection for geological disposal

There is considerable experience in several countries with regard to site selection from which lessons can be learned. During the early stages of site selection for a spent fuel repository, the process was led by geological surveys and public opposition was encountered when borehole drilling began at sites. In the 30 years since, it has been necessary to work on building confidence through stakeholder engagement and greater transparency. A strong technical basis has been developed with all technical work published and there have been early and regular interaction between the implementer and regulators, as well as extensive contact with the public to encourage dialogue. Whilst there is a tendency for site selection to be focused on technical criteria, informed by site characterization data, several sites were identified as being suitable and the site was eventually therefore chosen based on a broad range of considerations.

In Norway, a site selection process took place in the 1980s for geological disposal of low-level waste and short-lived intermediate level waste. Disposal is above ground level within a rock cavern located within a small mountain. There was limited consideration of the deep geology in the area. A process for the selection of a site for deep geological disposal of higher activity and longer-lived wastes has not yet been established and there is no recent experience in site selection. As such, it may be necessary to start from the very beginning in defining the process and experience from Sweden and Finland will be useful in informing the process.

Norway has only small volumes of radioactive waste, but a wide range of wastes. It may be feasible to develop a single repository, but with multiple disposal concepts for the different wastes. If this were to move forward, the location and design of different parts of the facility would have to consider effects on other parts. For example, excavation could affect water flows in another part of the facility and, if organic wastes were to be placed in one part, the design would need to ensure that these could not significantly migrate into other parts of the system where they could mobilize contaminants or otherwise critically damage the containment system.

5.5.4 Developing and maintaining competencies

Operators and regulators need competence to deal with decommissioning, legacies and radioactive waste and it is recommended that, whilst regulators should be independent of operators, a close working relationship be fostered and maintained in order to allow decisions to be made on all sides on a fully informed basis. This applies to understanding of regulatory requirements by operators and understanding of technical and other challenges by regulators. Early engagement is necessary to develop a common understanding of needs and priorities. Where there are different regulators for different aspects of a project, their respective roles, responsibilities and interactions may need to be clarified. Regulations may also need to be revised and/or developed to address specific circumstances that may not have been taken into account in previous regulatory development.

There is concern generally around available competencies for dealing with decommissioning, legacy sites and radioactive waste management since the competencies required may be different from those for operational facilities. Those competencies also need to be maintained for decades into the future as programmes continue. Understanding of the history of site operations and events is already an issue in many parts of the world as the generation involved in the building and operation of facilities retires. Scientific support relevant to decommissioning, legacy sites and radioactive waste management has declined, with universities tending to focus on more popular subjects and it can be difficult to attract students into the nuclear field. Those who do study in the field may not remain in the country in which they gained their education. There is, therefore, concern on how knowledge and experience can be maintained in the long-term.

5.5.5 Communicating uncertainties

Uncertainties associated with the results of safety and other assessments can be difficult to communicate without causing alarm to the general stakeholder. For example, uncertainties can be very large, but still not significant in terms of meeting safety requirements, if the result is still well below safety criteria. One approach that is often used is a worst-case approach to illustrate that even in a worst-case scenario the outcome is acceptable and within regulatory requirements but, by focusing on the worst-case, there is a risk that understanding of what is actually likely could be lost. There is also a risk that people could think that what was considered as a worst-case will happen Impacts should only be presented alongside some assessment of their likelihood. Furthermore, use of an overly cautious approach could result in resources being applied disproportionately to the level of actual risk.

6 Overall Conclusions and Recommendations

The workshop provided an opportunity to bring together regulators and operators, to share experience of practical challenges faced and different perspectives on what is important and what is still needed in terms of making and reviewing safety cases, and how the scientific community can help in addressing those challenges. The working group discussions were very productive in building on the presentations made. The mix of experience within groups and the different disciplines represented allowed discussion around cross-cutting issues. Such an approach is considered very beneficial since, when addressing decommissioning, legacy and waste management issues, experience has shown that a multi-disciplinary approach is needed to address the diverse hazards and issues that may be present.

The following overall conclusions and recommendations are drawn.

- Key contaminants from research reactors and related facilities can differ from those typically associated with commercial reactors and information on their characteristics is often lacking. Even for the more common contaminants, knowledge on their behavior can be lacking for ecosystems that are quite specific to Scandinavian scenarios, such as mires. As such, there would be merit in identifying key contaminants (both radioactive and chemical) for which information on environmental behavior is lacking for key Nordic environments. Research projects could then be developed and undertaken to provide necessary knowledge and data in support of safety assessments.
- Research reactors present their individual challenges, with each being different. Nonetheless, there is the opportunity to learn from the experience of others in developing safety cases from an operator’s perspective and in their review from the perspective of regulators. It could be useful, therefore, to review past experience and consider lessons learned in terms of what worked well, what were the key challenges faced, what prevented decisions from being made (e.g. the key uncertainties), and how that knowledge and experience can be used to support decommissioning programmes for research reactors. Research activities could also be identified that would help address challenges that could arise during research reactor decommissioning, including data and important knowledge gaps. Importance here can be measured by whether the gap affects a decision.
- There is also the opportunity to look further into lessons learned with regard to site characterization strategies, including effective stakeholder engagement. Characterization is a vital part of any decommissioning, legacy or waste management programme and considerable experience has been gained in several different countries. By gathering together experience and reviewing lessons learned about what to characterize and how and when sufficient characterization has been achieved, consideration could be given as to whether a framework for site characterization could be developed that would provide support to those involved in future programmes, whilst still recognizing that each situation will present unique challenges.
- Stakeholder engagement continues to be an issue for many programmes and there would be benefit in drawing together experience of how stakeholder dialogue has been approached and implemented in different programmes, what did or did not work well, and what issues were faced and the causes of those issues. Focus could be given to key technical areas and how the main messages are communicated, and dialogue encouraged, with different stakeholders, from members of the public to politicians, noting that communication about risk can be a particular challenge. From this, consideration could be given to the development of a framework for effective stakeholder engagement that is based on real-world experience and lessons learned.
- There is a tendency in research programmes to focus on single issues or topics. There may be merit, however, in taking a more cross-cutting approach whereby several issues are considered together with discussion looking more widely at the issues in order to find the optimum way forward that takes account of the range of issues faced. As an example, a research project could look at how to carry out effective dialogue between relevant stakeholders that addresses different hazards and risks.
- The use of a harmonized and proportionate approach to decommissioning, legacy and waste management is commonly referred to. However, developing and applying such an approach is challenging. Decommissioning and legacy sites are often associated with a wide range of radiological, chemical and physical hazards and complex social contexts. In order to take a holistic and proportionate approach to managing those hazards, risks need to be characterized and ranked, and approaches to addressing the prioritized risks should be optimized. Often, however, different

regulations apply and there may be different regulatory bodies overseeing the management of different hazards, which adds to the challenge. Nonetheless, there would be merit in drawing together experience of approaches that have been adopted or adapted to address these issues. This would also support the identification of research that would support the development and application of harmonized and proportionate assessments of risk from different hazards. There is also an opportunity to consider harmonization of approaches between countries through the development of a common framework. The optimum solution may be locally specific, but the method to identify and implement it can include common features. In addition, adoption of a common approach is likely to offer its own benefits. Such benefits need to be weighed against the advantages of local flexibility.

- Finally, continued exchange of science information across Nordic countries is considered very beneficial. This could take the form of a collaborative forum that brings together operators, regulators and the scientific community to continue to discuss the challenges faced in decommissioning, legacy and waste management programmes in different countries and to identify common research needs that can be supported through shared resources. Such an approach can help secure the necessary funds to allow academic research to progress whilst avoiding issues arising from perceptions that research is not sufficiently independent. The provision of funds for academic research on widely acknowledged, but particular, scientific questions could also help in developing necessary skills and competencies.

7 References

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Appendix A. List of Participants

The workshop participants and their affiliations are provided in the following table.

Name	Organization
Violeta Hansen	Aarhus University
Tobias Lindborg	Blackthorn Science
Line Diana Blytt	COWI
Mikkel Øberg	Danish Decommissioning
Lillemor Claesson Liljedahl	Danish Hydrological Institute
Emma Lindborg	Danish Hydrological Institute
Vendi Andersson	DSA
Ian Barraclough	DSA
Solveig Dysvik	DSA
Kristin Elise Frogg	DSA
Anne Marie Frøvig	DSA
Marte Holmstrand	DSA
Hilde Knapstad	DSA
Victoria Sevenoaks	DSA
Malgorzata Sneve	DSA
Per Strand	DSA
Naeem Ul Syed	DSA
Ari Ikonen	EnviroCase, Ltd.
Matti Kaisanlahti	Fortum Power and Heat Oy
Ismo Aaltonen	Geological Survey of Finland
Graham Smith	GMS Abingdon and Clemson University
Jørn-Harald Hansen	IFE
Knut Bjørnar Larsen	IFE
Jan Wethe	IFE
Frøydis Wærsted	NGI
Øystein Nordgulen	NGU/CERAD
Ann-Karin Olsen	NIPH/CERAD
Knut Erik Tollefsen	NIVA/CERAD
Simon Jerome	NMBU/CERAD
Helen French	NMBU/CERAD
Ole Christian Lind	NMBU/CERAD
Deborah Oughton	NMBU/CERAD
Estela Reinoso-Maset	NMBU/CERAD
Brit Salbu	NMBU/CERAD
Lindis Skipperud	NMBU/CERAD
Yevgeniya Tomkiv	NMBU/CERAD
Nina Ramberg	NND
Lasse Moe-Fredriksen	NND
Erik Berge	Norwegian Meteorological Institute/CERAD
Sarah Watson	Quintessa Limited
Karen Smith	RadEcol Consulting Ltd
Ulrik Kautsky	SKB
Martin Amft	SSM

Henrik Efraimsson	SSM
Leif Jonasson	SSM
Ove Nilsson	SSM
Helene Wijk	SSM
Johan Rydberg	Umeå University
Marja Siitari-Kaupp	University of Helsinki
Markus Airila	VTT
Nadezhda Gotcheva	VTT
Erika Holt	VTT
Suvi Karvonen	VTT
Pekka Viitanen	VTT
Marja Ylönen	VTT

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dsa@dsa.no
+47 67 16 25 00
dsa.no

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DSA Regulatory Support to Kazakhstan, Kyrgyzstan and Tajikistan, 2017–2020

2 DSA-rapport 02-2021
Luftovervåkningsrapport 2020

3 DSA Report 03-2021
Risk and safety assessments supporting regulatory supervision of decommissioning and waste management for nuclear research and radiation facilities.

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