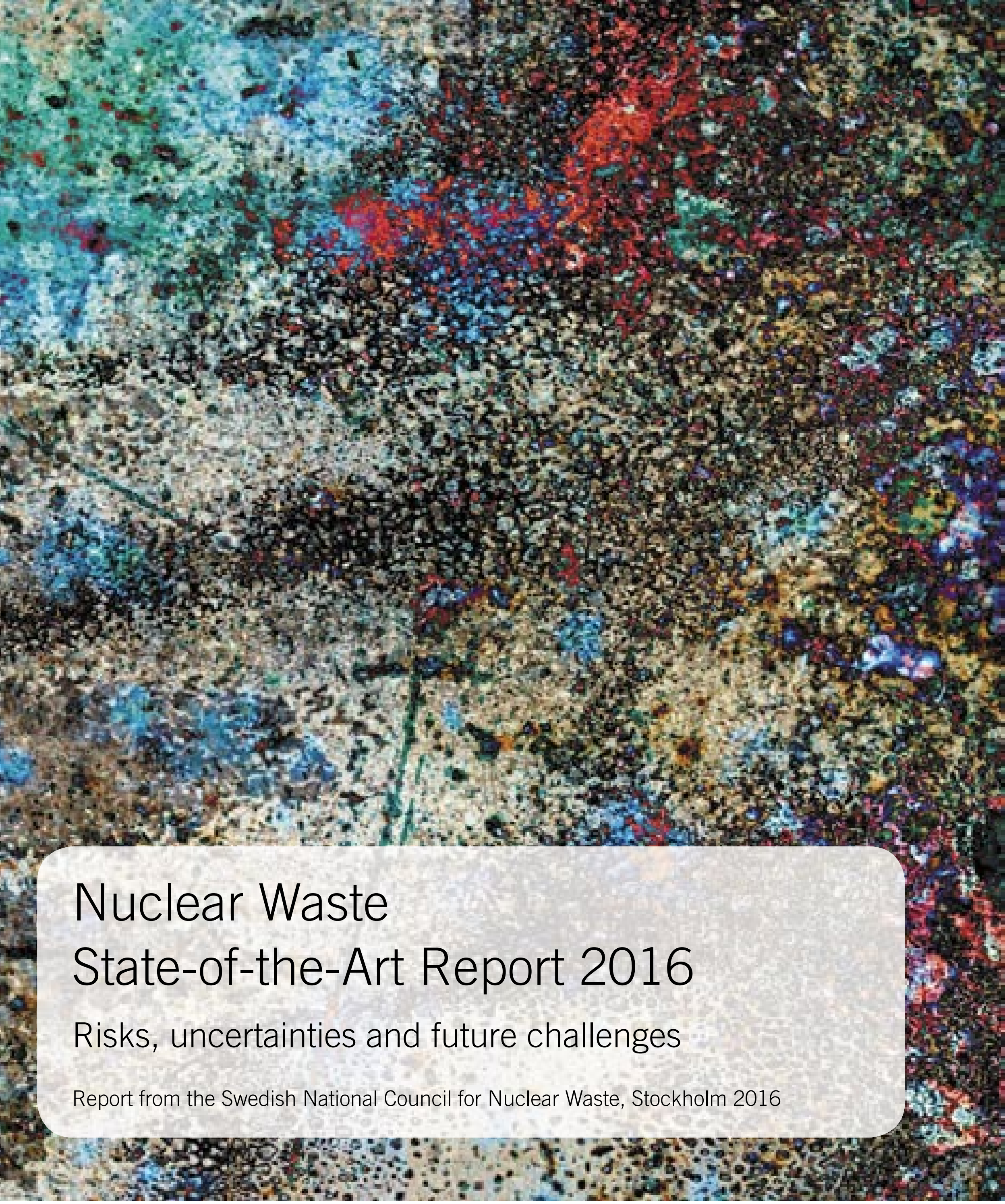

Nuclear Waste State-of-the-Art Report 2016

Risks, uncertainties and future challenges

Report from the Swedish National Council for Nuclear Waste, Stockholm 2016

KÄRNAVFALLSRÅDET
Swedish National Council for Nuclear Waste

SWEDISH GOVERNMENT INQUIRIES

SOU 2016:16

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Translation of SOU 2016:16

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The Swedish National Council for Nuclear Waste

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To the minister and head of the Ministry of the Environment and Energy

The Swedish National Council for Nuclear Waste is an independent scientific committee whose mission is to advise the Government on matters relating to nuclear waste and decommissioning of nuclear facilities. In February each year, the Council publishes its independent assessment of the current state of the art in the nuclear waste field. The assessment is presented in the form of a state-of-the-art report. The purpose of the report is to call attention to and describe issues which the Council considers important and to present the Council's viewpoints on these issues.

The Swedish National Council for Nuclear Waste hereby submits to the Government this year's state-of-the-art report (the sixteenth in this series) entitled *Nuclear Waste State-of-the-Art Report 2016. Risks, uncertainties and future challenges.*

This report is endorsed by all members and experts in the Swedish National Council for Nuclear Waste. English versions of the reports on the state-of-the-art in the nuclear waste field for 1998, 2001, 2004, 2007, 2010, 2011, 2012, 2013, 2014 and 2015 are also available.
Stockholm, 29 February 2016

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1 Introduction

1.1 Notable events in the field of nuclear waste in Sweden during 2015

Several issues relating to the management of radioactive waste were discussed in the Swedish public debate during 2015. The review of the Swedish Nuclear Fuel and Waste Management Co's (SKB) application to build a final repository for spent nuclear fuel and an encapsulation plant in the municipality of Oskarshamn has proceeded in accordance with revised timetables. The Swedish Radiation Safety Authority (SSM) and the Land and Environment Court at Nacka District Court (the Land and Environment Court) now expect to submit their review statements to the Government in 2017.

The Swedish Radiation Safety Authority's issue-specific review of the applications under the Nuclear Activities Act is under way, and SSM gave public notice of the applications on 29 January 2016. During 2015, SSM published preliminary results from its ongoing review in four reports. SSM has pointed out that the published results are preliminary and that it is still too early to draw any conclusions concerning the results of the SSM's overall assessment.

The Land and Environment Court at Nacka District Court gave public notice of SKB's application on 29 January 2016, at the same time as SSM. Concerned public authorities, organizations and interested parties can submit viewpoints on the matter to the Land and Environment Court by not later than 30 March. According to the current timetable, the main hearing will begin in October 2016.

The cost aspects of decommissioning and dismantling of the facilities and management of the spent nuclear fuel and radioactive waste have been discussed in the public arena and by the concerned parties. The Nuclear Waste Fund's annual report for 2014 shows that the predicted disbursements to defray the costs of nuclear waste management have increased more than the Fund due to the low level of interest rates. According to the chairman of the Nuclear Waste Fund, Daniel Barr, the Fund, which has been set up to finance the decommissioning of the Swedish nuclear power system, is short SEK 11 billion (Dagens Industri, 26 June 2015). The decisions to shut down the nuclear power reactors Oskarshamn 1 and 2 and Ringhals 1 and 2 earlier than planned will have an impact on the Fund. By reason of these events, SSM submitted a communication to the Ministry of Environment and Energy on 2 December 2015 proposing an increase in the nuclear waste fee.

Given the long project period for a final repository for spent nuclear fuel, from the start of construction until its final closure, competence in the final repository field will be required for several generations to come. The delays that have already occurred in the processing of the applications, along with political decisions in the nuclear power field, have also raised the issue of preservation of current competencies and future competence management. The issue is examined in this report with respect to competence requirements for the final repository project.

The management of low- and intermediate-level waste (LILW) has received attention during the year. SKB has submitted applications to SSM and the Land and Environment Court to build the final repository for low- and intermediate-level short-lived waste (SFR). The question of how to manage and dispose of waste from the decommissioning and dismantling of the closed reactors has been raised in the wake of decisions to move forward the decommissioning of reactors in Oskarshamn and Ringhals. The two reactors in Barsebäck are already shut down, but dismantling has not begun pending the availability of facilities for disposal of the decommissioning waste. According to SKB's timetable, the planned final repository for long-lived radioactive waste (SFL) will not be commissioned until 2045.

1.2 Content of this year's state-of-the-art report

The Swedish National Council for Nuclear Waste's mission is to advise the Government by, for example, identifying notable events in the nuclear waste field and shedding light on issues relating to nuclear waste and the decommissioning and dismantling of nuclear facilities in an annual state-of-the-art report. The report examines a number of questions which the Council considers important to clarify in the Swedish final repository programme. These questions are dealt with in the following chapters:

National competence management of importance for the final repository

This chapter examines issues relating to competence preservation and competence management in areas of relevance for a final repository for spent nuclear fuel. A point of departure is the review of the competence need within the radiation protection field which SSM carried out for the Government for the purpose of identifying any problems, and where necessary make proposals for measures to secure national radiation protection competence in the long term.

The Council notes that the report is an example of a larger question that embraces a number of disciplines of relevance for the planning of the final repository for spent nuclear fuel during the operating period as well as after closure, which could lie 80–100 years in the future. There is a need during this long period of time to ensure competence among licensees, regulatory authorities and activity operators. In addition, demands are made on universities and HEIs (higher education institutions) that they be able to deliver educational services on a broad front.

Obligations and responsibilities in connection with decommissioning and dismantling

This chapter describes the legal regulatory framework governing obligations and responsibilities in connection with decommissioning and dismantling of nuclear power reactors. These matters are examined in the light of the requirements of the Nuclear Activities Act and the Environmental Code, as well as from an economic perspective.

Examples of such questions are what impact the early closure of nuclear power plants will have on the Nuclear Waste Fund and what the premises are for a safe management and disposal of radioactive waste and spent nuclear fuel.

Ethical perspectives on the agreement on support to the municipalities

This chapter discusses the ethical aspects of added-value initiatives, compensation programmes and other support to local communities that are considering participating in consultations regarding different final repository projects. The question of compensation to the local communities that host the final repository for spent nuclear fuel within their borders can be approached from many different vantage points.

After a brief review of these aspects, the ethical issues raised by such programmes are examined. Can we formulate some ethical principles to make an assessment? Are the proposed principles applicable – and if so, how? And how, against this background, should the Swedish added-value programme be judged? The review leads to the conclusion that the programme is ethically acceptable and meaningful from several perspectives, even though the Council finds that some individual elements may be ethically problematical.

Earthquakes and earthquake risks in Sweden

This chapter describes occurrences and causes of earthquakes in Sweden. They are discussed in relation to SKB's safety assessment of a final repository for spent nuclear fuel. There was an unusually powerful earthquake in Sveg in 2014, and the chapter examines how an earthquake of that magnitude could impact the final repository.

Risks and effects of low doses of radioactivity on man and environment

This chapter examines the risks and health effects to which man and the environment are exposed by low doses of ionizing radiation. Furthermore, a general description is provided of the knowledge on which the risk estimates are based and the uncertainties involved in estimating the risks of exposure to low doses of ionizing radiation.

The chapter describes how radiation risks arise and how great these risks are to man at a given radiation dose. Risks associated with radiation from a final repository for spent nuclear fuel are discussed, along with various scenarios for the effects on the environment if the limit values for the final repository are exceeded by up to a thousandfold. The chapter also discusses what lessons can be learned from previous releases of radioactive substances to the environment, intentional or unintentional, with a focus on the nuclear disaster in Chernobyl and the releases in the southern Ural Mountains. Finally, the chapter describes the issues that have been the subject of the past thirty years of research in the area and what the research front looks like when it comes to radiation protection.

Strategies for monitoring programmes in planned final repositories

The question of monitoring and surveillance of final repositories has been examined by the Council in previous reports and seminars. Monitoring programmes for surveillance in sealed areas were discussed in last year's state-of-the-art report. The focus then was on international efforts to develop new measurement technology and plans for technical installations in sealed areas to measure the state of the engineered barriers and the rock in the excavation-damaged zone.

This year's report focuses on strategies for monitoring. Important questions are why measurements in sealed areas are needed, the design principles for such programmes, and how the results can be used, but also how conflicts with regulations governing long-term safety can be avoided. The point of departure for the discussions is completed and planned EU projects, but study visits have also been made to Posiva's demonstration repository in Finland, and the plans for monitoring in Switzerland have been studied.

This chapter was written by Willis Forsling and Clas-Otto Wene, former members of the Swedish National Council for Nuclear Waste.

1.3 The work of the Swedish National Council for Nuclear Waste and international cooperation in 2015

The composition of the Council has changed during the year with the addition of two new members: Ingmar Persson, Professor of Inorganic and Physical Chemistry at the Swedish University of Agricultural Sciences (SLU) in Uppsala, and Mikael Karlsson, environmental researcher at the Royal Institute of Technology (KTH). At the end of 2015, Karin Högdahl asked to be relieved of her post as Vice Chairman of the Council, but will continue as an ordinary member. The new Vice Chairman is Tuija Hilding-Rydevik.

State-of-the-Art report 2015

According to Directive 2009:31[1], the Swedish National Council for Nuclear Waste shall describe the previous year's work and present its independent assessment of the current situation in the nuclear waste field in an annual State-of-the-Art Report. Last year's state-of-the-art report (Swedish National Council for Nuclear Waste, 2015a) was submitted in February to Yvonne Ruwaida, State Secretary at the Ministry of Environment and Energy. The state-of-the-art report was presented at an open seminar in Stockholm in March 2015. The Council published newsletters from the seminar on such subjects as nuclear safeguards, monitoring programmes, information and knowledge preservation and cost calculations. The Council also presented the contents of the state-of-the-art report at an open seminar in Östhammar Municipality in May.

[1] The Council shall also investigate and shed light on important issues in the nuclear waste field, for example by holding hearings and seminars, so that it can make well-founded recommendations to the Government. The Council shall keep track of other countries' programmes for management and disposal of nuclear waste and spent nuclear fuel and shall also follow and, if necessary, participate in the work of international organizations in the nuclear waste field.

SKB's application for a final repository for spent nuclear fuel

The Council continued to follow the processing of SKB's application for a licence to build a final repository for spent nuclear fuel during 2015. The Council submitted its viewpoints to the Land and Environment Court at Nacka District Court on 26 June with clarifications of previously submitted viewpoints on the need for supplementary information. The Council's statement reiterated several of the viewpoints which the Council had previously noted, above all the viewpoint that the application documents submitted to the Land and Environment Court for examination under the Environmental Code should contain the same information as the documents submitted to SSM for examination under the Nuclear Activities Act. This also applies to the supplementary information submitted by SKB to SSM.

SKB's application to extend the final repository for short-lived low- and intermediate-level waste (SFR)

At the end of 2014, SKB submitted an application to the Land and Environment Court at Nacka District Court and to SSM for a licence to extend the final repository short-lived low- and intermediate-level waste (SFR). The new repository will primarily serve as a repository for short-lived low- and intermediate-level radioactive waste, but will also be used as an interim storage facility for long-lived low- and intermediate-level waste until the final repository for long-lived radioactive waste (SFL) is built, which, according to SKB, will be in about 30–50 years.

The Council has followed this work and submitted viewpoints in September 2015 on the need for supplementary information to the Land and Environment Court in February and to SSM. In its statement to the Land and Environment Court, the Council reiterated viewpoints previously expressed in statements to SKB, to the effect that the applied-for activity should be treated as a new activity and not just an extension of an existing activity (Swedish National Council for Nuclear Waste, 2011, 2014, 2015b). This distinction is essential for the continued process, since new construction requires the Government's permissibility assessment and furthermore provides an opportunity for Östhammar Municipality to say yes or no to the extension (Chap. 17 Sec. 6 of the Environmental Code). Östhammar Municipality has expressed the same opinion in its statements.

In the statement to SSM, the Council points out that SKB does not present an alternative solution for how to manage the long-lived waste that is planned to be interim-stored in SFR if SFL is not built or is greatly delayed (Swedish National Council for Nuclear Waste, 2015c).

Ongoing activities, meetings and seminars

The Council has held 6 Council meetings and a number of meetings with its target groups, including SSM, municipalities, the Ministry of Environment and Energy and the Centre Party, plus a round-table meeting with organizations financed by the Nuclear Waste Fund.

State-of-the-Art Report 2015 was presented at an open seminar in Stockholm on 24 March, and newsletters were published from the seminar. In cooperation with the National Committee for Radiation Protection Research, the Council arranged a seminar at the Royal Swedish Academy of Sciences (KVA) on 3 November 2015 entitled: *The radiation risks for a final repository for spent nuclear fuel. What will the consequences be for man and biota if the dose limit is exceeded?* Chapter 6 in this year's report is based in part on this seminar, as is Newsletter 2015:2 *Importance of research on the risks at low radiation doses*, which is available on the Council's website (in Swedish only).

These meetings and publications provide a means for the Council to identify and investigate nuclear-waste-related issues.

International cooperation

The international dialogue is an important part of the Council's activities, and the Council has pursued discussions with e.g. advisory organizations in other countries.[2] In October, Council members travelled to the Czech Republic and met with the national Radioactive Waste Repository Authority (SÚRAO), the State Office for

[2] Advisory Bodies to Government (ABG).

Nuclear Safety (SÚJB), and an interdisciplinary reference group that is participating in the ongoing consultation process.

The Council's members have taken part in various international conferences, for example the Waste Management (WM) Conference that is held annually in Phoenix, Arizona, and a seminar arranged by the NWTRB in Washington, D.C. in November on a research project for deep borehole disposal of radioactive waste.

The Council has also participated in the work of the OECD's Nuclear Energy Agency on nuclear waste management, above all in the *Forum on Stakeholder Confidence*, which is chaired by the Council's Executive Director, Holmfridur Bjarnadottir.

The Council has also shared its experience with British waste disposal experts; Karin Högdahl is a member of the Geological Society's *National Geological Screening Independent Review Panel* and the Council's Executive Director is a member of the *Community Representation Working Group* (CRWG) under the Department of Energy and Climate Change.

International events

Finnish government issues licence to Posiva Oy

On 12 November 2015, the Finnish government issued a licence to Posiva Oy to build an encapsulation plant and final repository for spent nuclear fuel at Olkiluoto.[3]

Posiva is planning to build a final repository for spent nuclear fuel on the Olkiluoto peninsula in the municipality of Eurajoki in western Finland. Posiva has built a research tunnel near Olkiluoto in the Onkalo bedrock, which is also planned to be a part of the final repository.

Posiva Oy is owned by two of the Finnish nuclear power reactor owners, Teollisuuden Voima Oy (60 percent) and Fortum Power & Heat Oy (40 percent). The company is responsible for the management and disposal of the owners' spent nuclear fuel, analogous to SKB's mission. Posiva's application for a final repository for spent nuclear fuel is largely based on the Swedish KBS-3 method, and they have cooperated closely with SKB in their research. The Finnish

[3] Press release 12 Nov. 2015: http://valtioneuvosto.fi (downloaded 1 Dec. 2015).

final repository project is described in Chapter 7 in connection with the discussion of strategies for monitoring programmes in sealed areas. The Government attached several conditions to the construction licence. In conjunction with its application for an operating licence, Posiva must submit studies of environmental consequences, the retrievability of the spent nuclear fuel, and the risks associated with transport, as well as any changes made in the project.

Workshop on deep borehole disposal, Washington, D.C., 20−22 October

On 20–22 October 2015, the US Nuclear Waste Technical Review Board (NWTRB) held a workshop in Washington, D.C., entitled "International Technical Workshop on Deep Borehole Disposal of Radioactive Waste." The purpose was to obtain information on the Department of Energy's (DOE) plans for the deep borehole disposal project that started in 2015. The NWTRB's purpose was also to tap into whatever expert knowledge exists concerning deep boreholes in and outside the USA. Sweden was represented by the Swedish National Council for Nuclear Waste, the Swedish NGO Office for Nuclear Waste Review (MKG), SKB and SSM.

The DOE started a project in 2015 where they plan to drill two boreholes in crystalline rock down to a depth of 5,000 metres. The first borehole will be about 8 cm in diameter at a depth of 5,000 metres. Geology, geochemistry and hydrology will be studied at this depth. The DOE also plans to drill another hole down to a depth of 5,000 metres, but with a bottom diameter of about 43 cm. The purpose of the larger-diameter borehole is to evaluate drilling methods and costs for drilling to these depths. No waste will be emplaced in any of the boreholes. The project will also evaluate canister material, deposition, sealing and closure. The DOE plans to begin drilling in the autumn of 2016. The project will last five years and currently has a budget of USD 80 million.

The DOE is studying deep boreholes in order to evaluate whether it is possible to dispose of radionuclides such as cesium and strontium in a deep borehole repository. The quantities of waste to be disposed of in the USA would fit into one borehole. The Swedish National Council for Nuclear Waste is following the DOE project and other research on deep boreholes. The Council provided an overview of the state-of-the-art for Deep Boreholes in State-of-the-Art Report 2014.

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2 National competence management of importance for the final repository for spent nuclear fuel

This year we would like to draw particular attention to the need for national competence management in areas of relevance for a Swedish geological repository for spent nuclear fuel. We at the Swedish National Council for Nuclear Waste perceive this to be an area where there is a lack of national coordination and control, in spite of far-reaching plans to start both encapsulation activities and regular operation of a final repository during this century. This is a huge undertaking, with national responsibility that spans over a long period of time. In order to ensure the safety required by law, it is vital that Sweden as a nation can guarantee that the competence needed for this undertaking will exist within the country during this period of time.

The purpose of the chapter is to initiate a discussion of national competence management, rather than to provide an exhaustive description of what these competences are, or how they are to be managed.

2.1 Introduction

In 2015, the Swedish Radiation Safety Authority (SSM) published the report *Nationell kompetens inom strålskyddsområdet* ("National competence in the radiation protection field," in Swedish) (SSM, 2015) in response to a Government appropriation direction. The purpose was to clarify possible competence gaps in the field of radiation protection and where necessary propose measures to secure national radiation protection competence in the long term. The report identifies a number of competence gaps in the radiation protection field at the national level:

I. Too few of SSM's employees possess knowledge of radiation protection at a high international level. There is a lack of cutting-edge expertise, and there are a couple of identified areas in which SSM currently has no competence. There is a risk that important problems will not be identified, evaluated or resolved, that actual injuries may occur and that confidence in the Authority will be compromised.

II. In activities where radiation protection competence is needed, the authors note that research and education/training resources within certain relevant areas have diminished, resulting in a narrow competence base. At the same time, other previously identified competence gaps have to some extent been addressed by specially targeted funding.

III. As far as research and education is concerned, the authors point out that the educational opportunities within some research areas have decreased and are now judged to be subcritical. The research is being conducted by small groups or individual researchers with very limited funding. The authors of the report believe that the fact that radiation protection is an interdisciplinary subject and not separate field may make it more difficult to compete for resources.

The report focuses on competence in the field of radiation protection, where areas such as radiation biology, radioecology and radiation dosimetry are singled out as being particularly critical in terms of survival. The report has aroused concern within the Swedish National Council for Nuclear Waste, which has discussed to what extent the problems identified by the report exist in other areas as well. It is likely that this is a narrow cross-cut from a much larger issue. As an example of another neglected area, which has not been investigated, we can mention the field of nuclear and solution chemistry. Sweden was a world leader in solution chemistry up until the 1980s, but the leading expertise that existed in this area has largely been eradicated today, with the exception of certain individuals at Chalmers and other universities, who are however approaching the end of their careers. This in itself entails a competence problem for the future.

Among Swedish universities, only the Department of Chemistry and Chemical Engineering at Chalmers has a laboratory that meets the requirements for working with highly radioactive isotopes. Competence at this laboratory is high for work with materials that are of central importance for nuclear-waste-related issues. Funding of these activities is dependent today on external grants from EU projects, since previous support from e.g. the Swedish Nuclear Fuel and Waste Management Co (SKB) has nearly dried up. Chalmers and the Royal Institute of Technology (KTH) both offer postgraduate studies in nuclear chemistry. Aside from this, regular courses in solution and nuclear chemistry are no longer offered at the undergraduate level at any Swedish university. Nor are regular courses offered in these subjects in the postgraduate programmes at Chalmers and KTH, but only as needed internally.

Chalmers recently declared its interest to the Swedish Research Council to apply for funds to create an infrastructure of national interest to foster research on radioactivity at other higher education institutions (HEIs). Swedish competence in the field of nuclear chemistry is concentrated to Chalmers, and to some extent to KTH.

2.2 Competence from a final disposal perspective – the importance of competence management to meet future needs

Just like in the radiation protection report (SSM, 2015), we conclude that training/education and research are extremely important for long-term maintenance of a satisfactory national knowledge base. Furthermore, the connection between education and research is vital for maintaining the quality and relevance of the education.

In addition to their primary tasks of research and teaching, our academic researchers also have a duty to pursue what is known as public outreach, which involves promoting public awareness and understanding of science and technology. Research is of central importance, since it contributes to knowledge development and competence growth. The research task is the main reason why competent personnel apply for positions at, or remain at, Swedish universities and HEIs, which also enables the institutions to educate both undergraduate and doctoral students, while pursuing public outreach. Thus, without adequate funds for research it is not possible to maintain or raise today's level of competence.

Undergraduate education, postgraduate studies, contract training/education and in-service training are different types of training and educational programmes offered by universities and HEIs. Undergraduate education involves education at the basic level and leads to a B.A., M.A. or M.Sc. Eng. degree. Postgraduate studies provide the specialist education that leads to a Ph.D., and contract/in-service training is training with a certain focus aimed at improving the student's knowledge within a selected area.

It is important for us to be able to deliver all of these different kinds of education and training at a national level in order to be able to supply nuclear licensees, public authorities and society at large with well-educated and competent personnel. This requires researchers and teachers at universities and HEIs who can deliver such educational services. This is important both when during the planning and operating stages of the final repository, but also post-closure. Nor should we forget that the competence that is considered relevant for a final repository also has a bearing on many other areas in society, including the social sciences, the natural sciences and technology.

2.3 Responsibility, coordination and funding

Responsibility

According to the above description, which is far from complete, there are palpable risks that the competence that exists in areas essential for nuclear waste management in Sweden is eroding due to reduced research funding and a dwindling selection of courses in these areas at Swedish universities and HEIs. In view of this, it may be warranted for Swedish public authorities to review the prevailing situation, where no national funding body seems to be taking responsibility for maintaining current competence and raising the level of knowledge in these areas. Without measures to address these problems, we may eventually find ourselves in a situation where our academic experts have abandoned their research fields due to a lack of funding. This would be devastating for the education of our future professionals and researchers and our society as a whole.

Already today, the situation is such that no one has overall responsibility for these matters, and the view that this is someone else's responsibility appears to be widespread. The Council cannot readily answer the question of how this has come about, but would like to suggest that perhaps the Government should be more clear in its instructions to SSM regarding how to deal with the issue of competence management.

Coordination

The radiation protection report (SSM, 2015) is a clear and good example of an area of competence that is being addressed nationally in order to fill any gaps. Education and competence in the field of nuclear engineering at KTH, Chalmers and Uppsala University have also been investigated by SSM, which notes that research funding has already declined and that it will decline further in the future. The situation can is said to be similar to that in the 1990s, when the industry decided to support the academic community, except that now the power companies are losing money and do not have the same resources. In its report, SSM offers recommendations regarding e.g. increased support to the HEIs and points out that targeted initiatives may be needed in order to attract promising students to doctoral programmes.

While national and coordinated analyses are unusual, it is common for various enterprises to conduct their own competence analyses and provide in-house training to fill the competence gaps. The report raises a number of new questions, of which the most obvious is *How many other areas are there of relevance to final disposal that are in need of a similar analysis?*

It is possible to take different approaches in addressing this problem. One is to rely on different actors with a stake in the final repository to make their own (in-house) analyses of competence needs. If all goes well, they should discover and address the competence gaps and so as to meet any long-term needs. But can we rely on our academic researchers – who deliver the needed specialist competence and keep society supplied with the necessary repository-relevant education and training programmes – to find sufficient funding for their continued existence on their own?

No difficulties will arise if everything goes as planned, but what if something goes wrong? If the actors in the sector rely on in-house training, what do we do if the knowledge does not exist in-house? How will we gain access to new research findings, and to what extent can we make use of them; how public will these results be, and to what extent will new knowledge be scrutinized and peer-reviewed as meticulously as scientific results are today? And what will we do if the relevant specialist competence no longer exists in the academic community, or if the level of competence is too low due to cutbacks, or if researchers have gone abroad or switched to other fields and specialists in industry and government have retired?

A future where we have a final repository for spent nuclear fuel but do not have adequate competence in the field, including relevant educational programmes, is a daunting prospect. In order to avoid such a situation, we must look at the whole picture and make sure that the specialist competence that will be needed can in fact be delivered.

Funding

Research at Swedish universities and HEIs is funded in different ways. Internal funding includes faculty funds and teaching funds, but these funds are very limited in most cases and cover only a small portion of payroll and other costs.

Most of the research funding comes from external sources. Major Swedish research funding bodies include the Swedish Research Council, the Swedish Foundation for Strategic Research, Formas, Vinnova and the Swedish Energy Agency. When it comes to funding for radiation protection research, the Swedish Radiation Safety Authority is an important source, albeit of limited scope. The different funding bodies have different demands on the research they fund. All funding bodies prioritize projects of high excellence. Certain funding bodies primarily give money to basic research and not research aimed at a specific application, such as a final repository for spent nuclear fuel, while others prioritize innovative and entrepreneurial research, which does not make for a very good fit for nuclear waste disposal either. The Swedish Energy Agency basically funds all energy-research except that which is fission-related, which might be considered an odd attitude. Some of the Swedish Research Council's calls for proposals exclude fission-related research as well. SSM, on the other hand, funds technological and natural science research in repository-related subject areas, as well as some social science research in the area of MTO/Human factors[1]. However, SSM's budget is so limited that it can hardly shoulder all responsibility for competence management within the broad field embraced by a final repository for spent nuclear fuel.

In summary, the shortage of competence in repository-related subjects is due to the lack of a strategy for funding of research in this interdisciplinary area. Is this situation acceptable, and who assumes responsibility for the consequences?

2.4 International perspective

International networks

The nuclear chemistry field has an extensive European network, which in turn has good contacts with Japan and the USA in particular. The European network has been successful in obtaining EU funding, which has been a prerequisite for research activities in Sweden, given the weak support currently available from Swedish funding bodies.

Radiation protection training in Europe

The problems facing competence management in radiation protection in Europe have been noted, which has led to various training initiatives within the framework of the Euratom programme[2] (see below). These problems stem from the fact that the number of European countries with their own research in radiation protection

[1] The subject of how and man, technology and organization (MTO) interact, also known as "human factors".
[2] The European Atomic Energy Community's (Euratom) framework programme research and training in the nuclear energy field.

has been drastically reduced during the past decade. The decline is particularly marked in certain areas such as radioecology, but the number of European research groups in radiobiology is also declining. The situation in most European countries is even more problematical than that in Sweden, which had led Euratom to launch programmes for competence development in radiation protection during the past 6 years.

Euratom is the single biggest funding body for radiation protection research at universities and research institutions in Europe. The European Commission sponsors multiannual "framework programmes", of which the latest, which replaces Framework Programme 7, is called Horizon 2020 and includes Euratom's funding initiatives. Euratom has several programmes, of which NFRP7 has a special bearing on competence development in areas related to the final repository for spent nuclear fuel.

Under NFRP7, available funds for 2015 have been granted to a consortium called CONCERT[3], which is intended to fund research projects as well as training courses. This programme can be regarded as a continuation of the training programme that was started under FP7 and within the framework of a project called DoReMi[4], where courses have been offered in different areas of radiation projection research.

The purpose of these initiatives is primarily to give countries without their own training courses an opportunity to maintain some basic competence in radiation protection.

The research funds announced via CONCERT will be allocated in keen competition between different research groups in the EU. Countries with their own national programmes in radiation protection have clear advantages when it comes to competing for these funds. This further increases the gaps within the EU with regard to radiation protection competence, where a small number of countries are successful in obtaining grants.

Most of these grants end up in France, Germany, Belgium and the UK, with the national radiation protection authorities, while grants to European universities have declined. This has already led to a reduction in national capacity for training and education in

[3] http://www.concert-h2020.eu/en/Calls/ET_Call_2015 (downloaded 1 Dec. 2015).
[4] http://www.doremi-noe.net/training_and_education.html (downloaded 1 Dec. 2015).

radiation protection, including in the above countries, since most such training and education takes place at the universities.

To achieve the competence level needed to build and maintain a final repository for spent nuclear fuel, national research programmes are needed in the natural sciences, the humanities and the social sciences, in combination with a strategy for the transmission and preservation of knowledge.

2.5 Conclusion

To return to the central question of competence management in areas of relevance to nuclear waste disposal, it can be noted that there appear to be gaps in areas of vital importance in both the short and long term. The Swedish National Council for Nuclear Waste therefore finds it urgent that some public authority be assigned the task of identifying the areas of competence that are necessary for a safe Swedish geological repository for spent nuclear fuel and conducting a survey of the quality of education and research within these areas at Swedish universities and HEIs. Such an analysis of the competence need and available competence within the country should provide the basis for a broad discussion, which includes the Government Offices, to determine what additional resources are needed in relevant areas of research and education to meet the radiation protection requirements on a geological repository for spent nuclear fuel.

This should be done promptly, since we see that today's experts and researchers are either switching fields, moving abroad or retiring. This represents a serious competence drain, which in turn will have consequences when adequate resources are no longer available for the education and further in-service training of new experts. Moreover, we risk finding ourselves in a situation where targeted funds are allocated too late when there are no longer any researchers or research groups left to apply for them.

In its capacity as an advisory body to the Government, the Swedish National Council for Nuclear Waste offers to assist in the important process of securing the necessary future competence in the nuclear waste field.

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3 Obligations and responsibilities in connection with decommissioning and dismantling of nuclear power reactors

The question of how a nuclear power reactor that has been permanently shut down and is in the process of being decommissioned should be defined came up during the Swedish National Council for Nuclear Waste's hearing "Decommissioning of Nuclear Facilities in Sweden" on 11 December 2007 (Swedish National Council for Nuclear Waste, 2007). In other words: when does a nuclear power reactor cease to be a nuclear power reactor?

The answer to the question made reference to the EU's so-called EIA directive. According to this directive: "Nuclear power stations and other nuclear reactors cease to be such an installation when all nuclear fuel and other radioactively contaminated elements have been removed permanently from the installation site" (Council Directive 97/11/EC, Annex I, point 2).

This means that all spent nuclear fuel and radioactively contaminated material, such as parts of the reactor containment, must be removed and placed in a final repository, or alternatively in an interim storage facility pending final disposal. Only then does the reactor cease to exist.

This chapter is a follow-up to the hearing that was held eight years ago.

3.1 The licensees for the Swedish nuclear power reactors

The Act (1984:3) on Nuclear Activities (the Nuclear Activities Act) regulates nuclear activities. The Act uses the expression “nuclear activities” as a collective term for what it covers. The term is of central importance for the systematics and scope of the law and is particularly important because conducting nuclear activities without a licence is prohibited.

Operation of nuclear power reactors is a nuclear activity which thus requires a licence under the Nuclear Activities Act. Decommissioning and dismantling of nuclear power reactors is included in the concept “operation of nuclear power reactors”. In addition to a licence under the Nuclear Activities Act, operating a nuclear power reactor also requires a licence under the Environmental Code.[1] The Environmental Code also requires a special licence to begin decommissioning and dismantling of the reactor (see below).

There are four companies that have licences under the Nuclear Activities Act and the Environmental Code to operate nuclear power reactors in Sweden. The four licensees are:

– Forsmark Kraftgrupp AB, which operates 3 nuclear power reactors in Östhammar Municipality,
– OKG AB, which operates 3 nuclear power reactors in Oskarshamn Municipality,
– Ringhals AB, which operates 4 nuclear power reactors in Varberg Municipality, and
– Barsebäck Kraft AB, which operates 2 nuclear power reactors in Kävlinge Municipality.

The two reactors in Barsebäck are permanently shut down and are undergoing shutdown operation and partial dismantling. The reactors will be dismantled when a final repository for long-lived radioactive reactor internals has been built. Consequently, Barsebäck

[1] In the case of new nuclear reactors, the Government shall, according to Chap. 17 Sec. 1 of the Environmental Code, assess their permissibility before a licence application can be considered.

Kraft AB also has a licence under the Environmental Code for decommissioning and dismantling of its two reactors.

A licence confers the right to own and operate the nuclear power reactors. The licence under the Nuclear Activities Act applies only to the licensee and no one else. This means it is not permitted to transfer a licence under the Nuclear Activities Act to another actor without first obtaining approval from the Government. Things are slightly different when it comes to a licence under the Environmental Code. According to the Environmental Code, the licence applies to the activity itself and is not tied to a given licensee, as is a licence under the Nuclear Activities Act.

There are also other important actors than the licensees in this context, namely those who own the nuclear power reactors in an economic sense. These are the parent companies in the groups to which the licensees belong. Their importance in this context is explained further on in the chapter.

3.2 The concept "permanently shut down nuclear power reactor"

The fact that a nuclear power reactor has been permanently shut down prior to decommissioning does not mean that the licence under the Nuclear Activities Act is no longer valid. The licence with its accompanying obligations remains valid until all obligations have been fulfilled. A permanently shut down nuclear power reactor awaiting decommissioning is still a nuclear power reactor, which furthermore requires a special licence under the Environmental Code in order to be decommissioned and dismantled – see below.

The Nuclear Activities Act contains a definition of the concept "permanently shut down nuclear power reactor". In accordance with this definition, it is: a nuclear power reactor where the activity involving the production of electrical power has ceased and will not be resumed, or a reactor that has not supplied electricity to the power grid over the past five years (cf. Sec. 2, point 4 of the Nuclear Activities Act). One of two situations may exist:

1. the licensee has made an active decision to permanently shut down the reactor, or
2. the reactor has for various reasons not supplied electricity to the power grid over the past five years, without the licensee having made an active decision to shut down the reactor.

There is no provision for any exceptions from the five-year rule (Gov. Bill 2009/10:172, p. 38).

This concept is of special importance when it comes to a licence to replace an old nuclear power reactor with a new one. The Government may only allow a new nuclear power reactor to be built if the new reactor is intended to replace a nuclear power reactor that will be permanently shut down when the new reactor is put into commercial operation.

Under the Nuclear Activities Act, a permanently shut down nuclear power reactor may not resume commercial operation (cf. Sec. 15 of the Nuclear Activities Act).

3.3 Obligation under the Nuclear Activities Act to undertake decommissioning measures

A licence under the Nuclear Activities Act for operation of a nuclear power reactor carries a number of obligations. The obligations include not only upholding safety during the operation of the reactor, but also ensuring that nuclear waste and spent nuclear fuel (nuclear material that is not reused) can be managed and disposed of in a safe manner.

The obligations also include ensuring that the nuclear power reactor is decommissioned and dismantled in a safe manner when it has been permanently shut down – see this concept below.[2] This entails complete dismantling and removal of the reactor and other devices in the reactor plant which are radioactively contaminated (cf. Sec. 10, first paragraph, of the Nuclear Activities Act).

[2] The concept "decommissioning" can be divided into the following phases: defuelling operation, shutdown operation and dismantling. "Defuelling operation" refers to the part of the decommissioning period when nuclear fuel is still present in the reactor, while "shutdown operation" refers to the period when all nuclear fuel has been removed from the site on which the reactor is located.

The obligation to decommission and dismantle the reactor persists until: “all operations at the facilities have ceased and all nuclear material and nuclear waste have been placed in a repository that has been sealed permanently” (cf. Sec. 10, first paragraph, point 3 of the Nuclear Activities Act). The law uses the phrase “sealed permanently” to define the point when the licensee’s responsibility has ceased to exist. The final repository issues are thus directly connected to the provision in the Nuclear Activities Act on the long-term obligations of the licensee.

As is evident from the Nuclear Activities Act, a licence to operate a nuclear power reactor is a very long-term commitment, both technically and financially. The Nuclear Activities Act emphasizes this by stating that the obligations incumbent upon a licensee shall remain even if the licence is revoked, the licence expires or a nuclear power reactor is permanently shut down until the licensee has fulfilled its obligations (cf. Sec. 14, first paragraph, of the Nuclear Activities Act).

In Sec. 14, second paragraph, the lawmaker has, however, provided that the licensee can in certain cases be released from his obligations. The following factors are considered in deciding whether such a release can be granted:

> the obligations incumbent upon the licensee can be fulfilled by another. In such a situation, it should also be determined whether the requirements on safety and safe waste management and decommissioning of the facility in question can be considered to be satisfied and that funds are available for this (Gov. Bill 1983/84:60, p. 94).

In this case, the Government may grant a release. (Cf. Sec. 17 of the Ordinance (1984:14) on Nuclear Activities).

3.4 Obligation to apply for a licence under the Environmental Code for decommissioning and dismantling

It is assumed under the Environmental Code that decommissioning and dismantling a reactor always leads to considerable environmental impact. The Environmental Code requires a special licence to decommission a nuclear power reactor or other nuclear reactor. The licence requirement is justified by the fact that decommissioning of a reactor is a long and complicated process that must be carried out under the supervision of the regulatory authorities. The Land and Environmental Court decides on the issuance of licences, pursuant to the provisions of the Environmental Code.

The licence under the Environmental Code applies to activities:

> whereby a nuclear power reactor or other nuclear reactor is dismantled or decommissioned, from the time the reactor is shut down until the reactor – after defuelling operation, shutdown operation and dismantlement – has ceased to exist due to the fact that all nuclear fuel and other radioactively contaminated materials have been removed permanently from the installation site (Chap. 22, Sec. 1 of the Environmental Review Ordinance [2013:251]).

According to the wording of the statute, the reactor has thus ceased to exist when all radioactively contaminated waste materials from the activity have been removed from the installation site.

In conjunction with the decision the court can also stipulate conditions for the licence. Notification shall also be made of the change in the activity, i.e. the decommissioning work, to the Swedish Radiation Safety Authority in accordance with the Authority's Regulations concerning Safety in Nuclear Facilities (SSMFS 2008:1. 2008:1). This means that more detailed provisions can be stipulated for the decommissioning work under both the Environmental Code and the Nuclear Activities Act. Since the Swedish Radiation Safety Authority exercises supervision over the activity under both the Environmental Code and the Nuclear Activities Act, this should not entail any coordination problems. A reactor that is to be decommissioned and dismantled is still a nuclear facility. The Authority can therefore continue to stipulate conditions and issue injunctions regarding safety and radiation protection for the decommissioning and dismantling work.

An environmental impact statement (EIS) shall be appended to an application to the Land and Environment Court. The EIS should identify and describe the direct and indirect effects which the decommissioning and dismantling work could have on people, animals, land, water, air, the climate, the landscape and the cultural environment, as well as on the management of land, water and the rest of the physical environment and on other management of materials, raw materials and energy. Furthermore, the EIS should enable an overall assessment to be made of these effects on human health and the environment and to identify and assess factors in the surrounding environment that could affect safety.

During the preparation of the EIS, the applicant shall consult with the County Administrative Board, state and municipal authorities, as well as with private citizens and organizations that are likely to be affected. The documentation surrounding the consultations shall be made available so that private citizens can offer viewpoints, which shall in turn serve as a basis for the standpoints adopted by the Land and Environmental Court.

In view of the fact that it is punishable by penalty (cf. Chap. 29, Sec. 4 of the Environmental Code) to start the decommissioning and dismantling work without a licence from the Land and Environment Court, it is important that a licensee begin the work by preparing an environmental impact statement in good time before an application is submitted to the court.

The Barsebäck Nuclear Power Plant, an example of decommissioning

The nuclear power reactors at the Barsebäck Nuclear Power Plant in Kävlinge Municipality just south of Landskrona were taken out of operation in 1999 and 2005 following a decision by the Government[3], with the support of the then-valid Nuclear Power Phase-Out Act (1977:1320). The law ceased to be valid on 30 June 2010. A licence for decommissioning and dismantling was required under the Environmental Code.

On 4 December 2012, after an application had been submitted by Barsebäck Kraft AB, the Land and Environment Court granted a licence to the company to pursue continued shutdown operation and partial dismantling, including segmentation and storage of reactor internals and construction of a storage building for storage of the internals, and renewed the permit for harbour activities at the nuclear power plant (Case no. M 2842-11).

The court judged, considering that shutdown operation and storage of internals would proceed for a limited time, that the environmental impact statement met the requirements on such a state-

[3] The Government's decision regarding Barsebäck 1 was made on 30 November 1999, and regarding Barsebäck 2 on 16 December 2004.

ment under the provisions of Chap. 6 of the Environmental Code and therefore approved the environmental impact statement.

Furthermore, the Land and Environment Court judged that there were no obstacles to a licence with reference to the general rules of consideration in Chap. 2 of the Environmental Code or the other provisions of the Code.

Several reviewing bodies, including the Swedish Radiation Safety Authority, had petitioned that the licence be time-limited. However, the Land and Environment Court judged that sufficient reasons do not exist to time-limit the licence, since shutdown operation must necessarily continue until construction of the final repository is finished.

3.5 Obligation to have financial resources and an organization that can complete the decommissioning

The objective of the safety work expressed in the nuclear activities legislation is to eliminate, as far as possible, the risks of a radiological accident and thereby ultimately the risk of losses of life or property. The requirements on safety and radiation protection are far-reaching. The Nuclear Activities Act can be said to have been designed to give the licensee nearly strict[4] responsibility for the operation of a nuclear facility, responsibility which cannot be transferred to someone else. Great weight is therefore attached to the licensee's capability to fulfil the obligations that accompany nuclear activity (see Gov. Bill 2009/10:172, p. 57).

The Nuclear Activities Act clarifies the licensee's obligations by requiring that the licensee have an organization with sufficient financial, administrative and human resources to ensure safe and reliable operation of the activity (cf. Sec. 13, first paragraph, point 2). The term "operation" also includes all activities associated with decommissioning and dismantling of a nuclear power reactor. The requirement that the licensee have an adequate organization also applies to any contractors hired by the licensee.

[4] It is thus not a question of strict responsibility on objective grounds.

The licensee is also obligated to have sufficient financial resources to carry out the measures required by the Nuclear Activities Act or by conditions or regulations issued pursuant to the Act, as well as protective measures in the event of operational disruptions or accidents at the facility (cf. Sec. 13, first paragraph, point 1). The licensee must be able to demonstrate credibly that it has the financial capacity required to meet the requirements in the form of sufficient share capital or financial guarantees by the parent company of the group to which the licensee belongs (if any). In this context, the licensee's obligations under e.g. the Nuclear Liability Act should be of great relevance (see Gov. Bill 2009/10:172, p. 57).

3.6 Financing of decommissioning and dismantling

The provisions of the Act (2006:647) on Financial Measures for the Management of Residual Products from Nuclear Activities (the Financing Act) provide some assurance that resources will be available for final disposal of spent nuclear fuel and decommissioning and dismantling of the nuclear power reactors. The purpose of the Financing Act is to ensure the financing of the licensee's costs for management and final disposal of the activity's residual products and the decommissioning and dismantling of the nuclear facilities, as well as the research and development that is necessary to achieve this.

To this end, the holder of a licence to own or operate a nuclear power reactor is obliged to pay a special fee – the nuclear waste fee. The nuclear waste fee is based on the total cost for management and disposal of the waste (including decommissioning and dismantling) generated by the reactor until the waste has been placed in a final repository (the *basic cost*).

This fee must also cover the state's costs for administration and supervision etc. of waste management (*extra costs*). The fee is paid by the owner of a nuclear power reactor in relation to the number of kilowatt-hours (kWh) of electricity delivered by the facility and shall cover a share of the costs that is equivalent to the licensee's share of all fee-liable licensees' residual products (cf. Sec. 7 of the Financing Act).

The obligation to pay the nuclear waste fee does not cease until all nuclear waste from an activity covered by the Act has been emplaced in sealed repositories. As a consequence, even licensees that have ceased their activities may be fee-liable for the measures that remain to be taken under the Nuclear Activities Act, such as management and disposal of nuclear waste and dismantling of facilities. The Act does not allow any exemptions; rather, release from fee liability follows indirectly from release from the obligations under the Nuclear Activities Act that is granted in accordance with its Sec. 14 (cf. Secs. 13 and 14 of the Financing Act).

More detailed provisions regarding the nuclear waste fee can be found in the Ordinance (2008:715) on Financial Measures for the Management of Residual Products from Nuclear Activities (the Financing Ordinance). The Ordinance provides that a reactor owner shall, in consultation with other reactor owners, prepare every three years a cost calculation as a basis for calculation of the nuclear waste fee (Sec. 3 of the Financing Ordinance). An assumption for the cost calculation is that every reactor that has not been permanently removed from service has a total operating time of 40 years. The remaining operating time must, however, always be assumed to be at least 6 years (Sec. 4 of the Financing Ordinance).

The Swedish Radiation Safety Authority shall, for each and every one of the reactor owners and based on the submitted cost calculation, prepare a proposal for the nuclear power fee which the licensee will pay for the next three calendar years. The proposed fee shall be specified in kronor per kilowatt-hour)(kWh) of electricity delivered (Sec. 6 of the Financing Ordinance).

SSM's proposal shall be submitted to the Government, which then determines fees and guarantee amounts for the next three calendar years. These periodic decisions regarding fees and guarantees every third year (rolling) are of central importance for taking into account new cost calculations, forecasts of nuclear power production, uncertainty assessments etc. and allowing these new estimates to influence the determination of new fees and guarantee amounts.

The fees are paid in to a government agency, the Nuclear Waste Fund, which also manages the Fund assets.

The party responsible for paying the nuclear waste fee must also pledge guarantees for the costs the fee is intended to cover, but which are not covered by the paid-in fees, plus an uncertainty margin to cover costs incurred by unplanned events.

The guarantees are intended to cover two different kinds of amounts:

1. financing amount: an amount corresponding to the difference between the remaining basic costs and extra costs for the waste products that have arisen at the time of the calculation and the funds that have been set aside for these costs,
2. supplementary amount: an amount corresponding to a reasonable estimate of costs referred to in Sec. 4, points 1–3 of the Financing Act that can arise as a result of unplanned events.

The guarantees are pledged in the form of joint and several guarantees by the parent companies of the licensees in question.[5]

3.7 Uncertainties in the financing system

As is evident above, the fees for financing the cost of management and disposal of the waste, including decommissioning and dismantling, generated by the nuclear power reactors are based on the total number of kWh of electricity delivered by the nuclear power plants. Each licensee shall cover a share of the costs that is equivalent to the licensee's share of all licensees' residual products.

According to SSM's communication *Regarding OKG AB's and Ringhals AB's decision regarding early shutdown of certain nuclear power reactors* (SSM, 2015), E.ON AB has decided to close the nuclear power reactors Oskarshamn 1 and 2 earlier than planned. Vattenfall AB has decided to close the reactors Ringhals 1 and Ringhals 2 earlier than planned.

An extraordinary general meeting of the shareholders at Vattenfall AB resolved that the Ringhals 2 reactor should be taken out of service on 13 July 2019 and the Ringhals 1 reactor on 14 June 2020. The previously planned dates for shutdown of the two reactors were 30 April 2025 and 31 December 2025, i.e. a reduction of the operating times by 5.8 and 5.5 years, respectively. This is equivalent

[5] In a joint and several guarantee, the guarantor undertakes full liability for the debt.

to a total reduction of the planned electricity output of the two reactors by 72 TWh.

Similarly, an extraordinary general meeting of the shareholders of OKG AB resolved that the Oskarshamn 1 reactor (O1) should be taken out of service and switched to shutdown operation some time during 2017–2019 instead of on 5 February 2022 as previously planned. The decision for the Oskarshamn 2 reactor (O2), which has been off-line since June 2013, means that the reactor will not be restarted, but will be classified as a permanently shut down reactor. For O1 this entails a reduction in operating time of 2.1 years, while for O2 it entails a reduction in operating time of 21.5 years. The total reduction in planned electricity output will be 145.1 TWh.

SSM has analyzed how OKG's and Ringhals AB's (RAB) decision to shut down the Oskarshamn 1 and 2 and Ringhals 1 and 2 reactors earlier than planned affects the financing of the future decommissioning and dismantling process. The changes in operating time which the licensees have decided on represent fundamental changes in the premises on which the Government's decisions on fees for the period 2015–2017 were based. In order to maintain balance in the financing system, the Authority estimates that the fee for OKG needs to be raised from 4.1 to 6.7 öre (1 Swedish krona = 100 öre) per kWh of electricity generated by nuclear power, and for RAB from 4.2 to 5.5 öre per kWh.

3.8 Conclusions

The parent companies own the nuclear power reactors, but financial responsibility rests with the individual licensees

Financial responsibility for the safe management and disposal of the nuclear waste generated by the nuclear power plants, as well as the their decommissioning and dismantling, rests with the individual licensees: Forsmarks Kraftgrupp AB, OKG AB, Ringhals AB and Barsebäck Kraft AB. These companies are owned wholly or partly by other companies or groups of companies. In this ownership structure, Vattenfall AB, E.ON AG and Fortum Oy are, to all intents and purposes, the top parent companies.

The parent companies in the groups of which the reactor owners are members do not hold the licences to own and operate the nuclear power reactors. In other words, these parent companies do not have any formal rights under the Nuclear Activities Act when it comes to the operation of the nuclear power reactors. Nor, more to the point, do they have any obligations when it comes to their decommissioning and dismantling.

The four reactor owners are pure reactor companies. The assets in these companies are essentially the nuclear power reactors, or, to put it another way, the future revenue from sales of nuclear-generated electricity. The profits from these sales are not accumulated to any great extent in these reactor companies. They are merely members of a group with little in the way of assets of their own.

There are no requirements on long-term financial strength linked to the licence to own or operate a nuclear power reactor. It is therefore a reasonable assumption that there will be no assets in the different reactor companies when they cease generating electricity. In other words, the reactor company itself does not have the long-term capability to fulfil the obligations defined by the Nuclear Activities Act regarding safe decommissioning and dismantling of the facilities and management and disposal of spent nuclear fuel and nuclear waste. The reactor companies (licensees), who bear responsibility under the law for final disposal of the spent nuclear fuel and safe decommissioning and dismantling of the nuclear power reactors, may cease to exist before the ultimate closure of the final repository.

Thus, considering the weak financial position of the reactor companies after the cessation of electricity production, uncertainty exists regarding the long-term capability of the licensees to fulfil their obligations. This includes their ability to pay upcoming nuclear waste fees for already generated waste and costs that may arise due to unplanned events.

The provisions of the Nuclear Activities Act entail that the licence to own and operate a nuclear power reactor may persist for many decades after the activities have actually ceased. But it is possible that the reactor owners that have generated the nuclear waste may cease to exist before all parts of the process of management and disposal of the spent nuclear fuel have been completed. When the reactors have ceased generating and selling electric power, these companies essentially no longer have any positive value (Financing Inquiry Report, 2004, section 4; SSM, 2013, section 4.9.2).

One conclusion may be that even though the rules in the legislation regarding obligations and responsibility for decommissioning of nuclear power reactors are clear, if several reactors are shut down earlier than planned, there may not be sufficient money in the Nuclear Waste Fund for decommissioning and dismantling. And what happens if a limited liability company with a licence for operating nuclear power reactors goes bankrupt? Who will pay for decommissioning and dismantling then? The parent companies of the groups of which the reactor owners are members bear no formal responsibility under the Nuclear Activities Act or the Environmental Code.

The principle for the financing of the costs to which the operation of the nuclear power reactors gives rise is that the licensees are liable for the costs in accordance with the “polluter pays principle”. Due to the uncertainties in the financing system, this principle is currently limited to a hope that the guarantees equivalent to the financing amount and the supplementary amount (see above) which the parent companies have helped their subsidiaries (the licensees) to pledge will cover the remaining costs in such a situation.

By ratifying the 1997 Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (the Nuclear Waste Convention), the Swedish state has undertaken ultimate responsibility to ensure that each such licensee shoulders its responsibility. If in the future there is no licensee or other liable party with the ability to shoulder this responsibility, liability rests with the state, which would conflict with the aforementioned “polluter pays” principle.

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4 Ethical perspectives on the agreement on support to the municipalities

4.1 Introduction

The question of special support to the local communities that have assumed the task of hosting a repository for spent nuclear fuel within their borders has been discussed in many countries. Different countries have chosen different forms of support. Subsidies aimed at roads, infrastructure and the labour market are some examples.

These programmes have been called added-value initiatives, compensation programmes or other names and can be studied from many different vantage points. It is possible to focus on the international situation and compare how different countries have designed their site selection processes and their support to local communities that have hosted or considered hosting a final repository for spent nuclear fuel. In this context, we will focus particular interest on the added-value agreement that was concluded in 2009 between the Swedish Nuclear Fuel and Waste Management Co (SKB), SKB's owners and the municipalities of Oskarshamn and Östhammar.

There are a number of reasons why this state-of-the-art report examines the motives behind this type of support programme, and in particular the Swedish added-value agreement. Social scientists have shown a growing interest in this question in recent years, and it has also been the subject of international research. Ethical issues have also been discussed in these analyses. A criminal complaint was lodged against Östhammar Municipality for receiving bribes from SKB, and while it has not led to any legal measures, the matter received media attention. Against this background, the Council decided to conduct an in-depth ethical analysis.

The chapter contains a brief review of how social scientists have described and explained the emergence of various support programmes in general, and a more detailed analysis of the ethical issues which such programmes raise in particular. Is it possible to formulate some ethical principles to permit an assessment of these programmes? What ethnical principles are relevant? How, against this background, should the Swedish added-value programme be judged?

The answer to these questions depends on how we describe phenomena such as compensation, added value and support initiatives. But confronting ethical issues inevitably involves judgements and tradeoffs based on values and opinions. The tone in this chapter is therefore one of discussion and debate.

The chapter is divided into six different sections. First a general description is given of the theoretical background to the different compensation and added-value programmes. Then SKB's added-value programme is presented, along with a brief international comparison. A general background is given to the ethical assessment of SKB's added-value programme, which is then discussed in greater detail in section 4.6 in relation to five ethical principles or conditions that have been formulated in the ethical debate of recent years. The chapter is concluded by a summary.

4.2 Background theories about compensation and added value

Agreements between waste disposal bodies and local communities have often been formulated in terms of compensation. This is true for different types of waste and different types of facilities, for example interim storage facilities and final repositories for spent nuclear fuel.

Compensation programmes have often been a part of the site selection process, but it is noteworthy that the Swedish cooperation agreement was signed only two months before SKB announced its decision to select Östhammar as the site for final disposal of spent nuclear fuel. SKB submitted its licence application in March 2011, and the Government is expected to make its decision no sooner than 2017, after the Swedish Radiation Safety Authority and the Land and Environment Court at Nacka District Court have ruled in the matter. But SKB also needs the approval of the municipalities, and the purpose of the cooperation agreement has been to facilitate such approval. This is also clear from the introduction to the cooperation agreement, where it says:

> The active participation of the municipalities is a prerequisite for the continued work and constitutes a basic premise for this Cooperation Agreement and for all added-value initiatives (Cooperation Agreement, section 1.4).

According to classical theory regarding compensation programmes, an imbalance initially exists between the benefits and risks of hosting e.g. a facility for the final disposal of spent nuclear fuel. Kojo and Richardson (2012) describe it in the following way:

> Opposition by nearby residents to the facility is assumed to be based on the idea that there is an imbalance between the high personal costs they are asked to bear relative to the benefits that accrue to a larger outside population. Thus these individuals would regard their losses to be outweighed by the benefits. The costs consist of different kinds of perceived risks and unwanted impacts. In compensation theory it is assumed that any negotiated benefit should be expected to redress the imbalance.[1]

Against this background, it is assumed that offers of compensation increase the willingness of the local population to permit projects that would otherwise be undesirable:

> To win the support of a prospective host community, the compensation has to be large enough to offset the net disutility imposed by the project. - - - The expected outcome of the theory is that any imbalance would be redressed and public opposition would abate.[2]

Now there are many signs that something is wrong with this theory. Kojo and Richardson note that, contrary to the theory, compensation programmes are often perceived not as fair payment for performance, but as bribery, something that substitutes crass market thinking for moral social responsibility.

One can also ask to what extent a cooperation agreement of the type concluded between SKB, SKB's owners and the municipalities

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[1] Kojo och Richardson, 2012, p. 8. Kojo and Richardson refer to two other articles by K. E. Portney and M. O'Hare.
[2] Kojo and Richardson, 2012, p. 8 f.

of Oskarshamn and Östhammar can be understood in the light of this compensation theory. In the introduction to the cooperation agreement, other considerations are mentioned than compensating the municipal residents for the risks entailed by a final repository. The agreement states, for example:

> The planned final repository for spent nuclear fuel and the encapsulation plant will be operated for a very long period of time, making it very important for SKB that these facilities are located in a well-functioning local community. Current nuclear activities in the municipalities … are also dependent on, for example, a well-functioning business community in order that the activities can be conducted in the best possible way. It is in the interest of the municipalities to develop such well-functioning local communities (Cooperation Agreement, 2009, section 1.5, translated from Swedish).

The theory described in this section can be described as *functionalistic*. The goal is a well-functioning local community. This is a prerequisite for a successful execution of the final repository project. The project cannot be isolated from social and economic contexts. Unless the labour market, schools, civil society, infrastructure etc. are well-functioning parts of an interacting whole, the premises for executing the complex and time-consuming final repository project will be undermined. In this respect, it can be assumed that the interests of the municipalities and SKB coincide. It is of course conceivable that these interests might diverge in the sense that SKB would prefer to invest in activities that benefit the repository project's organization and chances of success in a more immediate and direct fashion. Nevertheless, SKB and the municipalities may still have many common interests which the cooperation agreement should emphasize.

In contrast to this functionalistic theory, the compensation theory is based on a *conflict perspective*. The municipalities and SKB are assumed to have opposing interests from the beginning. SKB wants to build a final repository, which entails risks and drawbacks for the local residents. The local residents therefore demand fair compensation. SKB offers such compensation in the form of a cooperation agreement. The risk is that the compensation will be perceived as a bribe. Another drawback may be that the municipality's social responsibility is transformed into a matter of negotiation.

The added-value agreement is clearly in line with a more functionalistic perspective, while classic compensation programmes are based more on conflict theory. Whether or not the cooperation agreement actually fulfils and satisfies the commonality of interests that exists between SKB and the municipalities is another matter entirely. Nor can the possibility be ruled out that the functionalistic approach is used to prevent possible criticism of a compensation approach.

It could therefore be said that a functionalistic perspective paints a much too positive and uncritical picture of the Swedish added-value programme. With this in mind, it is important that the programme setup be subject to an unbiased ethical examination. In this context we will limit ourselves to an ethical assessment of SKB's added-value programme, starting with a brief presentation of this programme.

4.3 Cooperation agreement on added-value initiatives in Sweden

In 2007, the municipal leaders in Oskarshamn and Östhammar wrote a common letter to SKB proposing increased SKB support to the municipalities as compensation for their willingness to assume responsibility for the management of spent nuclear fuel. In 2009, a cooperation agreement was prepared between the municipalities of Oskarshamn and Östhammar on the one hand and SKB and its owners on the other. The agreement states that the parties:

> have considered it necessary to broaden the perspective and via cooperation create certain added values in order to contribute to the positive development of the municipalities of Oskarshamn and Östhammar, which is of great importance to SKB, SKB's owners and the municipalities (Cooperation Agreement, 2009, section 1.6, translated from Swedish).

The main points of this agreement have been summarized in the following manner by SKB's president, Christopher Eckerberg:

> The added-value agreement came into being at the initiative of the municipalities of Oskarshamn and Östhammar and entails that SKB and SKB's owners undertake to create added values amounting to SEK 1.5–2 billion in the municipalities. The municipality that SKB did not select for the final repository – Oskarshamn – gets 75 percent of the values and Östhammar gets 25 percent. The agreement was signed in 2009, just before SKB decided in which municipality they wish to locate the final repository. The agreement also states that the municipalities shall receive compensation for maintaining an organization to deal with these matters.[3]

About 20 percent of this added value will be created up until the time a licence has been granted for construction of a final repository, and the rest will be created thereafter, mainly up until 2025 (Co-operation Agreement, 2009, section 3, translated from Swedish). The added-value initiatives are decided by a steering group consisting of five members: the chairman, vice chairman and president of SKB, plus the chairman of the executive boards of Oskarshamn and Östhammar municipalities. Unanimous decisions are preferable, but if this is not possible decisions shall be made by a qualified majority, i.e. a majority of at least two votes.

The initiatives covered by the agreement are of a diverse nature. The following initiatives are mentioned in the cooperation agreement:

- Visitor centre
- Infrastructure
- Business development
- Spin-off activities
- Training and competence development
- Broadening of the labour market
- Further development of SKB's laboratories in Oskarshamn
- Special energy initiatives
- Head office functions
- Canister factory

[3] http://www.skbmervarden.se/ (downloaded 1 Dec. 2015).

- Energy production
- Special energy initiatives
- Compensation to the municipalities for participation in planning and execution of the added-value initiatives. (Cooperation Agreement, 2009, Appendix 1, translated from Swedish.)

A detailed account of the added-value initiatives decided on so far by the steering group is provided on SKB's website.[4]

4.4 International comparison

The cooperation agreement has equivalents in many other countries. Studies of these different types of agreements and more generally formulated programmes have been conducted within the framework of the EU project "Implementing Public Participation Approaches in Radioactive Waste Disposal (IPPA)"[5].

In a report from the IPPA project, two researchers – Matti Kojo and Phil Richardson – have presented a review of the international research on this type of programme since the end of the 1970s and have tried to clarify some terms that are used. Against the background and different case studies (e.g. in Poland, the Czech Republic and Slovenia), the authors also differentiate between different types of compensation programmes (Kojo and Richardson, 2012, p. 56; Richardson, 2010):

(1) cash incentives (e.g. in the form of a lump sum or annual payments),

(2) social benefit measures (e.g. funding of training or social projects),

(3) community empowerment measures (e.g. support to citizen groups, information and meeting activities).

[4] http://www.skbmervarden.se/mervardesprojekt/ (downloaded 1 Dec. 2015).

[5] IPPA was funded by Euratom's Seventh Framework Programme from 2011 up to the beginning of 2014. The project was focused on the nuclear waste programmes in Poland, the Czech Republic, Slovakia, Romania and Slovenia. Read more in (Swedish National Council for Nuclear Waste, 2014).

The authors adopt the "added value approach" as "an umbrella covering different elements of institutional mitigation, compensation and incentives in the site selection process" (Kojo and Richardson, 2012, p. 4).

Their intention is to broaden the discussion and draw attention to the increased emphasis on non-monetary initiatives in the form of social projects and different kinds of community empowerment measures. This is a strong argument for a renewed conceptualization, but unfortunately obscures the importance of the concept of added value in Sweden. In the Swedish cooperation agreement, added value has more to do with the financial return on investments made, i.e. the revenue that is generated for the municipalities as a result of the resources contributed by SKB (and possible co-financing from a third party).

SKB's and the municipalities' added-value projects cannot really be made to fit directly into Richardson's scheme. For this to be possible, it is instead necessary to consider the financial resources contributed by SKB to initiate different added-value initiatives. According to some calculations (from 2009–2015), the amount is about SEK 125 million.[6]

These initiatives can then be divided into cash incentives (mainly investments in the business community), social benefit measures and community empowerment measures.

[6] http://www.skbnu.se/investeringar-och-resultat/ (downloaded 1 Dec. 2015).

Morals and Ethics

Morals are our own notions about what is right and wrong, about what characterizes a good person, a good society and a good relation to nature.

Ethics can be described as our reflection on morals, i.e. the values we have and the actions we take. Why do I act the way I do? Should I act in some other way? Why do I embrace these values of right and wrong? What is a good society? What is a good relation to nature? Should I change my values? Ethics thus refers to our reflection on the content of our own and other people's morals.

All human beings have morals, i.e. notions of what is right and wrong – whether they are aware of these notions or not. But not everyone has ethics. Ethics entails taking a step back and reflecting on moral values (Swedish National Council for Nuclear Waste, 2004).

4.5 Added value and ethics

On 4 June 2015, a criminal complaint was filed with the police against Östhammar Municipality for receiving bribes from SKB. The complainant was a representative Swedish Anti Nuclear Movement. According to the complaint, the cooperation agreement is to be regarded as a bribe aimed at inducing the municipality to adopt a favourable attitude towards final disposal of the nuclear waste. The complaint was referred to the National Anti-Corruption Unit, which did not find reason to conclude that bribery had been committed. The cooperation agreement can be compared to a sponsorship agreement. No other crime was suspected, so the investigation was closed (Police, 2015, Reg. no. 5000-K685718-15).

There are thus no legal objections to the cooperation agreement. But that doesn't settle the ethical question. Many things are permitted under the law, but are not morally justified. There may thus be ethical objections to an added-value agreement, despite its legality.

Ethical analyses can be performed in different ways, and which way is the right way is open to discussion. In State-of-the-Art Report 2004, an extensive discussion is held about ethics and environmental ethics in the chapter “Nuclear Waste, Ethics and Responsibility for Future Generations” (Swedish National Council for Nuclear Waste, 2004). There the Council observes that analyses are often based on more general ethical principles. But it is also possible to postulate more specific conditions and test them to see if they can provide guidance in assessing e.g. the question of compensation to municipalities that have assumed responsibility for a final repository for spent nuclear fuel. This is the approach we will take in this context.

4.6 Ethical analysis of SKB's add-on agreement based on five conditions

Mike Hannis and Kate Rawles (2013) have carried out an ethical analysis which serves as a fruitful point of departure for an ethical assessment of the Swedish added-value agreement between SKB, SKB's owners, and the municipalities of Oskarshamn and Östhammar. Hannis and Rawles carry out their analysis by (1) formulating various conditions that should be met if an agreement is to be ethically acceptable, and (2) testing to see whether these conditions are useful and applicable to a particular compensation or added-value programme. It is important to emphasize that these conditions are merely a hypothetical starting point for the discussion. In some cases they may have to be adjusted in the light of special considerations, which we will explain in the presentation below.

We will use a slightly different terminology than Hannis and Rawles use and also introduce names for these different conditions. The first two conditions are formulated as follows:

1. **The non-persuasion condition**. The offer of reward must not be made with the intention of persuading the municipality to agree to be a host municipality for a final repository for spent nuclear fuel.
2. **The least-possible-risk condition**. The reward must not be offered as compensation for an action or decision that puts others at risk of harm[7] in a way that would constitute unethical

[7] The condition could of course be broadened to include other harm to animals and the natural environment. Animals and plants can be affected even if humans are not harmed (see Chapter 6, section 6.4.4).

behavior, or that is illegal, or that is unethical in other ways (Hannis and Rawles, 2013, p. 359).[8]

In addition to these two conditions, Hannis and Rawles discuss other considerations that can be formulated as three additional conditions.

3. **The independence condition**. The body that makes the offer of compensation must be, and be seen to be, genuinely independent from the nuclear power industry (ibid., p. 363 ff.).
4. **The condition of the public good**. It is ethically undesirable to transform a willingness to contribute to the public good into a financial relationship (ibid., p. 364 ff.).
5. **The condition of commensurability**. Accepting compensation must not entail a betrayal of the kinds of social relations or evaluative commitments that are constituted by "refusing to put a price on them" (ibid., pp. 366–371).

We will now comment on each of these different conditions and, in so far as is possible, determine whether they are applicable – and if so how – to the Swedish added-value agreement.

4.6.1 Comment on the non-persuasion condition

This condition is closely related to the charge made in the criminal complaint that was filed with the police in early June 2015. According to the complainant, the cooperation agreement was to be regarded as a bribe aimed at making the municipality favourably disposed towards the final disposal of spent nuclear fuel. It could be objected that if every action aimed at making a person or an organization more favourably disposed towards an agreement is a bribe – and thereby unethical – then every business deal would be unethical. In short: every form of persuasion cannot be regarded as unethical. This would be unreasonable.

[8] This condition could also be turned around: it is unethical for a municipality to demand compensation to "allow themselves to be persuaded".

This objection to the non-persuasion condition must be dealt with somehow. Hannis and Rawles share this opinion. One way is to reformulate the condition so that it does justice to the ethical intuitions to which the condition gives expression, but not in such a way that every attempt at persuasion is construed as a bribe or unethical behaviour. Hannis and Rawles suggest differentiating between (1) the actual *offer* of a reward and (2) the *reasons* which a municipality has for accepting a proposal from an industry to host a final repository. If there are good grounds for hosting a final repository that are independent of the rewards offered by the municipality, then the existence of these rewards and their influence on the municipal decision-making process are of less importance. With this in mind, the non-persuasion condition can be reformulated in the following manner:

> 1.1 There must be reasons for selecting a potential site that make sense independently of the compensation offer. These reasons will, presumably, take the form of a set of criteria referring to geological, geographical, and other features of potential sites. These criteria … should be informed by a process of public debate and deliberation, so that members of potential host communities will have been involved in the selection. The rationale behind the criteria should be transparent, well explained and understood to be robust.[9]

Hannis and Rawles write that "this argument is offered tentatively" and that "it would be a clearer case of compensation rather than bribery if the intention to influence judgment were not present".

But they state that the relevant factor is not the intention to influence the decision, but the presence or absence of independent grounds. For this reason, 1.1 is an acceptable ethical condition and allows the possibility that there may be ethically acceptable compensation programmes (provided that other relevant conditions are also satisfied).

We share this conclusion and believe that the Swedish added-value programme is ethically acceptable in an important respect. But three more detailed questions need further discussion.

The first question is whether SKB's intention with the added-value agreement has been to persuade the municipality to accept a final repository. In the opinion of the Council, this is not crucial

[9] Hannis and Rawles, 2013, p. 360.

from an ethical viewpoint. The important ethical question is whether the contents of the agreement are such that the agreement can be regarded as unethical.

But there is one activity in the cooperation agreement that could be regarded as problematic from an ethical viewpoint. The agreement states the following under the heading "Compensation to the municipalities for participation in the planning and execution of the added-value initiatives" (translated from Swedish):

> In order for the municipalities of Östhammar and Oskarshamn to maintain an organization that can participate in the added-value process and contribute to the work of realizing the added-value initiatives, SKB intends to pay one and a half million kronor per municipality and year during a ten-year period, starting in 2010. This amount is intended to be included in the aggregate added values (Cooperation Agreement, 2009, Appendix 1, p. 5, translated from Swedish).

According to a story on Swedish Radio's Program 4 on 4 June 2015, most of the salary paid to the business development manager in Östhammar Municipality is financed in this manner by SKB.[10] This was challenged, according to the same story, by Olle Lundin, Professor of Administrative Law at Uppsala University. He has two objections: *in the first place* there is a risk that this part of the agreement will "influence the public's judgement of the municipality so that they lose confidence in it and see it as being in the pocket of those who pay". *In the second place* there is a risk "that the person whose salary or job is paid for will – consciously or unconsciously – be influenced by where the money is coming from".[11]

In a *Comment on the matter presented*, the municipal director asserts the integrity of the municipality when it comes to leadership and coordination of the added-value programme.[12]

> All decisions, all disbursements, relating to how the municipality fulfils its obligation in the agreement, are made and executed by the municipal organization. This is done either by delegation or by our elected officials. Decisions, prioritizations and other policy actions are taken on the basis of municipal policy documents where the municipal

[10] http://sverigesradio.se/sida/artikel.aspx?programid=114&artikel=6181021 (downloaded 1 Dec. 2015).

[11] http://sverigesradio.se/sida/artikel.aspx?programid=114&artikel=6181021 (downloaded 1 Dec. 2015).

[12] Östhammar Municipality. 2015. Yttrande över inkommen fråga. ("Comment on the matter presented," translated from Swedish). AM-8080755[15.

> council's annual goals and budget documents occupy a special position (Östhammar Municipality, 2015, translated from Swedish).

It should, however, be noted that decisions regarding the added-value agreement are taken by the steering group whose members are the chairman, vice chairman and president of SKB, plus the chairman of the executive boards of Oskarshamn and Östhammar municipalities. According to SKB's organization chart, the business development managers in the municipalities of Oskarshamn and Östhammar are subordinate not only to the steering group, but also to the executive management of SKB.[13] In our opinion, Professor Olle Lundin's critical assessment is therefore not without relevance.

In the second place, it should be stressed that the intention of the cooperation agreement is to

> contribute to well-functioning transportation and infrastructure systems and a broadened labour market, and generally to create better conditions for personnel recruitment and competence development for the business community in the municipalities of Oskarshamn and Östhammar … (Cooperation Agreement, 2009, section 1.6, translated from Swedish).

Against this background, an example of an unethical added-value initiative could be an activity that does not – or is not expected to – create added value for the municipality in question. Determining whether or not this is the case with already-decided activities would require a special analysis and will not be done in this chapter. In general, the different types of added-value initiatives mentioned in the cooperation agreement appear to be of the character that considerable added value can be created. Ultimate responsibility for this rests with the steering group, whose function is described in detail in section 4 of the cooperation agreement. Of central importance are the preliminary studies ("feasibility studies") where possible activities are studied (and which are also published on the added-value programme's website). One would expect that calculations of a potential activity's added value would constitute an essential part of the feasibility study, but a cursory review of published feasibility studies shows that this is not the case. It is not clear if and where such assessments are made in other parts of the decision-making process.

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[13] http://www.skbmervarden.se/om-mervardesavtalet/(downloaded 1 Dec. 2015).

In the third place, an ethical evaluation of the added-value programme is dependent on the measures taken by SKB when the cooperation agreement was drawn up. Making an "offer that cannot be refused" is of course unethical, since it restricts the autonomy of the municipality. Examples of other unethical methods are deception, fear and ingratiation.[14]

However, there is no evidence that such methods of persuasion were used in connection with the preparation of the cooperation agreement between the municipalities and SKB. It was the municipalities who took the initiative to the agreement, not SKB.

4.6.2 Comments on the least-possible-risk condition

This condition is of central importance. One cannot compensate someone for agreeing to act unethically.

> If a person is persuaded by a reward to act unethically, the reward is a bribe and cannot be construed as compensation.[15]

Accepting to be the host for a final repository for spent nuclear also carries the additional complication that not only the well-being of the current generation, but also that of future generations must be considered. Everything depends on how serious the risk of harm is.

The non-risk condition touches upon the very heart of the final repository matter. SKB's application for a licence to build a final repository for spent nuclear fuel was submitted in 2011 and is currently being examined by the appropriate regulatory authorities. According to Hannis and Rawles, there are two ethical obligations that must be taken into consideration. *In the first place,* there is an obligation to minimize the risk of harm to current and future generations. In its application, SKB has presented arguments showing that it is possible to fulfil this obligation and that it can be fulfilled by

[14] It should be noted that there may be situations when deceit is ethically acceptable, for example concealing a surprise party from the person in whose honour the party is being given. Similarly, it is not unethical to use a moderate dose of fear to convince a child never to accept a ride from a stranger. Cheering up a friend who is depressed about a poor grade on a test could perhaps be perceived as ingratiating behaviour, but it is hardly an ethical problem in the same way as lavishing attention on a dying relative to persuade the relative to will her fortune to you. The examples are taken from: https://debate.uvm.edu/dcpdf/ada2013/convince/pers16_20060909102103.pdf (downloaded 1 Dec. 2015).

[15] Hannis and Rawles, 2013, p. 360.

means of the method and the site proposed by SKB. Naturally, the municipalities strive to conduct a thorough and objective assessment of these arguments, but they may be influenced by the different benefits offered by the added-value programme. This gives rise to an ethical dilemma: how should immediate added values be weighed against possible risks for future generations?

In the second place, there is also a risk that by agreeing to host a final repository, the municipal council also legitimizes, fully or partially, continued waste production, i.e. a future expansion of nuclear power. Hannis and Rawles write:

> There should therefore be an explicit and genuine attempt to keep the question of where and how an RWMF is to be hosted separate from the question of whether radioactive material should continue to be produced.[16]

A great deal can be said in favour of this viewpoint. In short, the question of nuclear waste disposal should be kept separate from the question of nuclear power generation. However, this is hardly possible in reality. And this is unfortunately related to the fact that the choice of final disposal method may be influenced by the possible use of the spent nuclear fuel in future nuclear reactors. There are reactor types on the horizon that could not only make use of spent nuclear fuel, but also reduce its volume and harmfulness. This question was discussed in State-of-the-Art Report 2011 and at the Council's international conference in 2012.[17] In this sense, the question of nuclear waste disposal is linked to the question of nuclear power generation. But it is nevertheless desirable to try to keep them separate *as far as possible*. A final disposal method could be chosen that permits, but does not necessitate, retrieval of the deposited nuclear waste.[18] According to SKB, KBS-3 is such a method.

[16] Hannis and Rawles, 2013, p. 362.
[17] www.karnavfallsradet.se/ (downloaded 1 Dec. 2015).
[18] See also (Swedish National Council for Nuclear Waste, 2013, Chap. 4).

4.6.3 Comment on the independence condition

As has already been noted, we fully agree with Hannis and Rawles that an offer of compensation as part of an attempt to persuade a municipality to accept a final repository is not in itself unethical. On the other hand, it is difficult to avoid the impression of a bribe if the person or organization making the offer has a great deal to gain from acceptance of the offer by the municipality. This is the main reason for the independence condition. This means that the body offering compensation to the municipality should be independent of the nuclear power industry. This would otherwise undermine the credibility of the offer of compensation.

But even though this argument may seem convincing, there are objections. *In the first place,* a body that is closely associated with the nuclear power industry – such as SKB – does not have to make an offer of compensation for something that can be perceived as unethical. It is an empirical question whether an offer is perceived in this way or not. Under certain circumstances, the nuclear power industry may enjoy a high level of public confidence, so that no shadow need be cast over an offer of compensation or an added-value programme.

In the second place, the public may find it natural and appropriate that the industry responsible for the nuclear power waste has an obligation not only to manage this waste but also to compensate the municipality that is willing to host a final repository.

It is a serious objection to a compensation programme if it can be perceived by municipal residents and others as a bribe – even if it isn't a bribe in strict legal terms. If the nuclear power industry or an industry that is closely associated with the nuclear power industry (such as SKB) is party to such an offer, they must credibly demonstrate that a compensation programme is not a bribe or otherwise unethical. This can be accomplished by ensuring that the municipality participates actively in the decision-making process leading up to a compensation agreement and that the municipality also has a considerable and legally established say in the distribution of the compensation resources (Hannis and Rawles, 2013, p. 360).

The cooperation agreement between SKB and the municipalities meets these requirements. The steering group includes two members from each of the municipalities of Oskarshamn and Östhammar.

This steering group has decided to distribute approximately SEK 125 million of SKB's resources to the two municipalities starting in 2009.

Furthermore, it should be noted that if the Government decides in favour of permissibility, most of the added value (75 percent) will be created in Oskarshamn Municipality and 25 percent in Östhammar Municipality, where the final repository will be built. The reason for this is that Östhammar will nevertheless gain considerable benefits from the final repository project. In the light of the independence condition, this reduces the risk that the added-value programme will be interpreted as a bribe or otherwise unethical. From an ethical viewpoint, this is a considerable advantage of the Swedish added-value programme.

There is, however, one problem with the decision-making process under the cooperation agreement. The agreement states that unanimous decisions are preferable, but if this is not possible a qualified majority is needed, i.e. at least four (of five) votes in favour. This means that an added-value initiative in Oskarshamn could be approved against Oskarshamn's will, but with the support of the three representatives from SKB and the representative from Östhammar. In practice this scenario is unlikely, but possible according to the rules of the cooperation agreement. It is also an ethically undesirable consequence since it limits municipal autonomy.

Another possible way to live up to the independence condition would be to finance a local added-value programme via a special fee and with a specially appointed public group to decide how the money should be allocated to e.g. items included in the present-day added-value programme. It would appear fully feasible to boost independence and transparency in this manner, while retaining a strong, but not exclusive, municipal and industrial influence over the decision-making process in such a body. Depending on the composition of the group, this would increase the likelihood of fulfilling both the non-persuasion condition and the least-possible-risk condition.

4.6.4 Comments on the condition of the public good

This condition ties in with the earlier discussion of classic compensation theory and its shortcomings. Kojo and Richardson assert that, contrary to the theory, compensation programmes are often perceived not as fair payment for performance, but as bribery, something that substitutes crass market thinking for moral social responsibility. There is also some empirical evidence that these fears are justified. Hannis and Rawles refer to a study by Ortwin Renn et al., who asked a representative selection of Swiss citizens if they were willing to permit the construction of a nuclear waste repository within the geographical boundaries of their community (Renn, Webler and Kastenholz, 1998).

They were then asked the same question, but with the additional information that parliament had agreed to financial compensation for all residents of the host community. In the first instance, 50.8% agreed to accept the repository. This dropped to 24.6% when financial compensation was offered. Hannis and Rawles summarize the results as follows:

> The authors of the study suggest that one possible explanation is that the compensation was perceived as a bribe, and the facility was rejected for this reason.[19]

Once again, it can be objected that there are differences between different types of compensation. Getting a sum of money as compensation for accepting a final repository for spent nuclear is one thing – being offered schools and fire stations in exchange is something quite different (Hannis and Rawles, 2013, p. 365 ff., where other studies are also cited in support of this difference).

This suggests that there is support for some kind of compensation to final repository municipalities in the form of benefits or goods instead of money. The compensation measures must be adapted to the kind of social relations existing between the party offering compensation and the party being offered compensation. Hannis and Rawles refer to an analysis done by the American social scientist Edmundo Claro. Claro distinguishes between three different ex-

[19] Hannis and Rawles, 2013, p. 364.

change relationships: communal sharing, equality matching and market pricing (Hannis and Rawles, 2013, p. 366; Claro, 2007).

The question of whether compensation is relevant or not depends on the nature of the exchange relationship. In another article, Claro provides an illustrative example. One person helps another to move house. If a son helps his father, this is taken to be a case of communal sharing. If one friend helps another, it is a case of equality matching and some kind of symbolic compensation may be appropriate. If a commercial removal company is engaged for the job, compensation is a question of market pricing. Claro clarifies how compensation should be approached when it comes to the siting of a spent nuclear fuel repository in the following manner:

> (I)f someone who frames the siting problem as a communal sharing one is offered money as compensation, she will react with anger and indignation, not only because the tradeoff is bizarre, but because it threatens fundamental aspects of her understanding of social relationships and society.[20]

This means that if compensation is offered in a society characterized by a strong communal ideal, it may be perceived as particularly provocative and as a kind of degradation of the social community to a market relationship.

Considering the Swedish situation, it may be natural to perceive the relationship between SKB and the municipalities not as a market relationship, but as an equality matching type of exchange relationship. In this view, an added-value programme is part of a fair distribution of resources in connection with the preparation and execution of the final repository project. What is being compensated is not primarily the risks entailed by the project, but rather the special measures undertaken by the municipality to ensure the successful realization of such a complex and long-term project. This brings us to the last condition.

[20] Claro, 2001; see also Hannis and Rawles, 2013, p. 366.

4.6.5 Comment on the condition of commensurability

If we choose to regard the relationship between the party offering compensation and the party being offered compensation as a market relationship, it can be described in terms of a cost-benefit analysis (in a narrower commercial sense). In this case it is assumed that all costs and benefits can and should be translated to monetary value (Hannis and Rawles, 2013, p. 367 ff.).

Such a cost-benefit analysis can be associated with an utilitarian ethic. Different outcomes are compared with each other, and the choice should fall on the alternative that leads to the most favourable balance of costs and benefits. Compensation is then to be regarded as an attempt to redistribute costs and benefits so that a reasonable balance is struck between costs (in the form of risks, charges or tasks) and benefits (in the form of various compensatory measures).

Hannis and Rawles are opposed to the utilitarian approach and to a compensation programme that rests on a cost-benefit analysis. They cite four different objections to this approach. The first objection has to do with the incommensurability between market relations and social relations. They refer to a paper by economist John O'Neill:

> (T)here are certain social relations and evaluative commitments that are constituted by a refusal to put a price on them - - - Given what love and friendship are, and given what market exchanges are, one cannot buy love or friendship. To believe one could, would be to misunderstand those very relationships. To accept a price is an act of betrayal, to offer a price is an act of bribery.[21]

The relationships O'Neill describes are a part of what is meant by a full human life. It is something you cannot put a price on in the commercial sense. And refusing to do this is a reaction to what those who are offered compensation perceive as a misunderstanding on the part of those offering the compensation. So far we concur with O'Neill, Hannis and Rawles. But from there to conclude that all forms of compensation or added-value programme "betray" the social relations that these programmes are all about is, in our opinion, going much too far. On the contrary, a compensation or added-

[21] O'Neill, 2007, p. 23, 25.

value programme can be described as an attempt to preserve such social relations, i.e.

> ... the relationships between those agreeing to host the management facility, their children, grand children and great grand children; and the relationships between these people and valued features of their local environment.[22]

This, of course, assumes that (1) the final repository in itself is safe for both the current and future generations, and (2) an added-value programme of the type agreed on between SKB and the municipalities is of such a nature that it effectively offsets other negative consequences of such a repository.

The second objection which Hannis and Rawles have to cost-benefit-determined compensation programmes is that they are not open to the possibility of non-financial assessments. They are based exclusively on subjective preferences and the cost-benefit calculations based on these preferences. But it is not reasonable to exclude a critical discussion of these preferences and thereby promote a discussion of e.g. whether they really contribute to creating the added values which there are intended to create, according to the added-value programme. This is fully in line with the Swedish added-value programme.

The third objection is a more general objection to utilitarianism as an ethical theory. Hannis and Rawles state that achieving the greatest balance of benefits over costs is perfectly compatible with the imposition of grave injustices on some people, or with the violation of their rights. This is a common objection to utilitarianism, which is beyond the scope of this report to deal with in greater detail. (See e.g. Tännsjö, 2000, p. 42 ff.). It should however be noted that it would be both possible and desirable to have such a discussion in connection with design and application of the Swedish added-value programme.

The fourth objection which Hannis and Rawles have to cost-benefit-determined compensation programmes is that they assume that there is always a right answer to all ethical questions. They assert instead that experience has taught us that certain ethical problems are unsolvable and that we must nevertheless take a stand. In short,

[22] Hannis and Rawles, 2013, p. 368.

we need an ethical perspective that promotes ethical sustainability. All options have ethical drawbacks, which suggests the need for:

> a continuous review of the circumstances that have led to our being compelled to choose from a set of options all of which are ethically problematic in some way.[23]

This observation can be linked to a concluding section in the cooperation agreement between SKB and the municipalities:

> The Parties are aware that the cooperation agreement aims at regulating the cooperation between the Parties during a long period of time and that changes in the cooperation agreement may be necessary, for example in the event of changed legislation, changed ownership structures within SKB, new regulatory requirements m.m. In the event of significantly changed premises for the cooperation agreement, the Parties will take up negotiations aimed at adapting the agreement to the new premises. All changes and additions to the cooperation agreement must be made in writing and signed by all the parties (Cooperation Agreement, 2009, 6.3, translated from Swedish).

The cooperation agreement could have been strengthened by including a section on regular evaluations and an assessment of whether the purpose of the agreement has been fulfilled and in what way the decided added-value initiatives have contributed to improving social and infrastructural development in the two municipalities. This could contribute to future improvement of the cooperation agreement.

4.7 Conclusions

In this chapter we dealt initially with the theoretical background of the research on compensation to local communities for permitting the construction and operation of e.g. a final repository for spent nuclear fuel. This analysis (albeit brief) seems to lead to two conclusions. The *first* is that there are drawbacks in the classic theories. These drawbacks are associated with the fact that the theories do not take sufficient account of the special social and evaluative relationships in the community and between the community and society at large. This cannot be fully described as a commercial market, but

[23] Hannis and Rawles, 2013, p. 371.

also as a duty-bound community. This explains why the expected appreciation of financial compensation for a final repository siting does not materialize.

The *second* conclusion is that an added-value agreement of the type that has been reached between SKB, SKB's owners and the two municipalities affected by the final repository project cannot be regarded as a compensation project in the usual sense. The purpose of the added-value agreement is to build up a social and economic infrastructure that enables the final repository project to be executed successfully. The added-value measures are aimed not only at technological development, but also development of the labour market, training and transportation.

In this chapter we have also taken a close look at the added-value agreement from an ethical perspective. Our point of departure has been the five ethical conditions that are expressed explicitly or implicitly in Mike Hannis's and Kate Rawles's important contribution in Deborah Outhton's and Sven Ove Hansson's anthology *Social and Ethical Aspects of Radiation Risk Management* (2013). We have named these conditions the non-persuasion condition, the least-possible-risk condition, the independence condition, the condition of the public good and the condition of commensurability. In more or less modified form, they are also applicable to the Swedish added-value agreement and have led us to the conclusion that this agreement is for the most part ethically acceptable from the perspective of these principles. To be sure, some elements can be questioned, and the Council emphasizes the need for a regular evaluation of the contents and application of the agreement.

Finally, the Council finds it urgent to point out that agreements of this nature involve both opportunities and risks. Provided that the final repository project is approved, the added-value programme has a potential to improve the chances for a successful execution of the project. At the same time there is a risk that the programme, with its strong incentives, may exercise a negative influence on safety-related and risk-related assessments. It is difficult to rule out the possibility that such a conscious or unconscious influence may exist. But these risks must not be allowed to overshadow the positive opportunities and benefits of the programme.

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5 Earthquakes and earthquake risks in Sweden

Earthquakes can cause great damage to buildings and infrastructure, nuclear facilities included, and they can trigger other natural disasters such as tidal waves (tsunamis) and landslides. This chapter describes what causes earthquakes and what an earthquake's magnitude is, as well as known earthquakes and the risk of major earthquakes in Sweden.

5.1 Background

Following the great earthquake in Japan in 2011, with a magnitude of 9.1, the IAEA recommends that a seismic risk assessment be carried out at all nuclear facilities. Despite the fact that Sweden and Finland are located in a low-risk area for powerful earthquakes, such an analysis was done for the planned nuclear power plant on the Hanhikivi peninsula in the municipality of Pyhäjoki in northern Finland (Korja and Kosonen, 2014), and at the urging of the Finnish Radiation and Nuclear Safety Authority (STUK), work was begun in 2014 on a seismic risk assessment for the existing nuclear power plants in southern Finland as well.

When an earthquake occurs, a displacement (slip) takes place along fractures in the bedrock. The length of this movement can range from a fraction of a millimetre to several metres, depending on the magnitude of the earthquake and the properties of the bedrock. In the case of a final repository for spent nuclear fuel, a powerful earthquake could open fractures in the rock and damage the buffer and canisters, with the risk that radionuclides will escape. The copper canisters in the KBS-3 method constitute a mechanical barrier between the waste and the bentonite buffer. According to

SKB, the copper canisters should be able to withstand a displacement of 5 cm, which could result from an earthquake, without their function being affected (SKB, 2011).

Earthquakes occur daily in Sweden. They are normally too small to be noticeable and can only be detected by very sensitive instruments called seismometers. The first seismic instrument in Sweden was installed in 1904, and today there are 65 permanent seismic monitoring stations around the country, which are operated by the Swedish National Seismic Network (SNSN)[1] at Uppsala University. SNSN records an average of about 600 earthquakes per year in Sweden, most of which have a magnitude <2.5. Owing to the sensitivity of the instruments, the number of earthquakes recorded increases with the number of stations.

The most powerful earthquake ever measured in or near Sweden was the Kosterö earthquake in 1904, also known as the Oslofjord earthquake. The earthquake occurred only weeks after the first Swedish seismograph was installed in Uppsala. Despite the fact that these early instruments were insensitive in comparison with modern seismometers, the earthquake was so powerful that it exceeded the seismometer's maximum level. The earthquake was also recorded by other instruments in Europe, and with the aid of these recordings its magnitude could be determined to be 5.4 on modern magnitude scales (Bungum et al. 2009). Methods also exist for estimating the magnitude of earthquakes that occurred before the installation of seismic instruments, known as historical or pre-instrumental earthquakes. In Sweden, this period extends back to the year 1375, and since then only one earthquake with a magnitude greater than 5 has been recorded, also on the west coast.

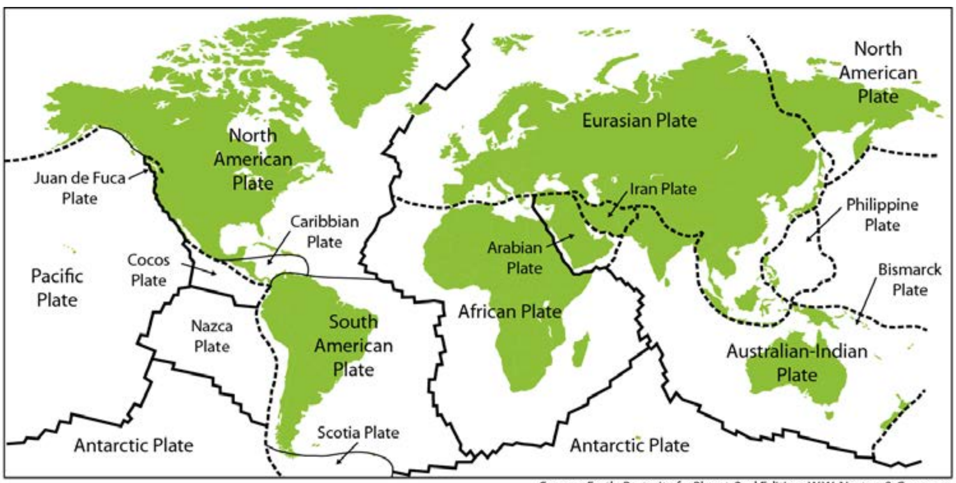
The natural earthquakes in Sweden are caused either by large-scale tectonic forces, or in conjunction with the readjustment of the Earth's crust that has been occurring since the retreat of the massively thick ice sheet following the last ice age. We will return to this later in the text.

[1] http://www.snsn.se/ (downloaded 1 Dec. 2015).

5.2 The cause of natural earthquakes

Powerful earthquakes occur primarily in the boundaries between lithosphere plates (Fig. 5.1), since the plates move slowly but steadily in relation to each other. The size and number of lithosphere plates has varied during the 4.5 billion year history of the Earth, and today there are seven major and 13 minor plates, plus a number that are less well-defined. Sweden forms part of the Eurasian Plate, to which most of the rest of Europe and mainland Asia also belong.

Figure 5.1 Lithosphere plates

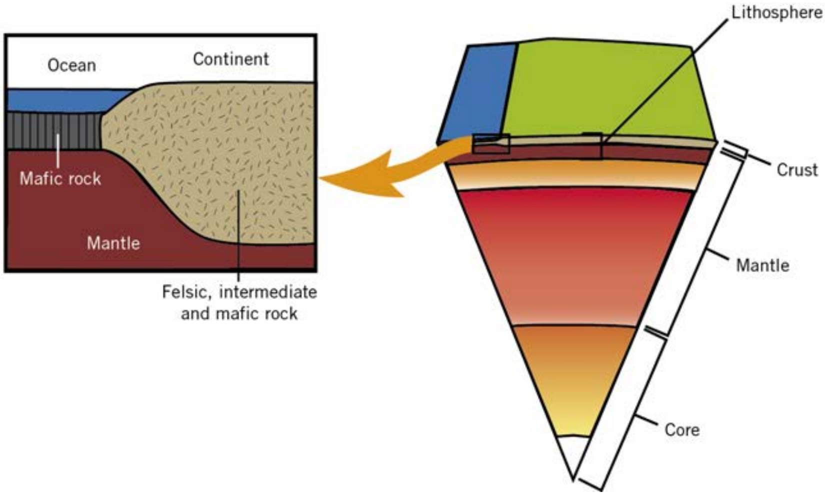


Sourse: *Earth: Portrait of a Planet*, 2nd Edition, W.W. Norton & Company

The Earth consists of seven major and 13 minor tectonic lithosphere plates. Sweden is located on the Eurasian Plate. The biggest horizontal rock stress in Sweden is caused by push forces originating in the Central Mid-Atlantic ridge, which is moving apart at a rate of 2–3 dm/year.

The lithosphere comprises the outer parts of the Earth and consists of the crust and the rigid upper part of the underlying mantle.

Figure 5.2 Cross-section through the Earth'



The Earth is divided into a number of zones, of which the outermost zone is the lithosphere, which consists of the rigid upper part of the mantle and the crust. The crust is lighter and thicker on the continents and thinner and heavier beneath the seas.

The lithosphere varies in thickness between 100 and 250 km and is generally thinner in sea areas that are dominated by an oceanic crust. The lithosphere is thickest in areas with old continental crust, such as in Sweden.

Earthquakes occur when stored elastic stress energy is released because the strength of the bedrock is exceeded and rapid displacements occur along old or newly formed fractures in the bedrock. The released energy generates different types of seismic waves, classified as *body waves* and *surface waves*. The intensity of both body and surface waves decreases with the distance from the point where the energy was released (the hypocentre or focus of the earthquake).

Body waves travel concentrically through the Earth from the focus in a manner similar to how sound waves propagate in solid materials. They consist of primary P-waves, which are propagated longitudinally by compression and dilation of the material through which the waves are moving, and by secondary transverse S-waves, which travel by means of oscillating movements perpendicular to the direction of propagation (Tarbuck et al. 2011).

The surface waves travel only along the surface of the Earth, both as vertical up-and-down wave movements, like waves on the sea, and as horizontal side-to-side (lateral) movements. It is the lateral movements that cause the greatest damage to buildings and infrastructure.

The most powerful and deepest earthquakes occur where two lithosphere plates collide, when the heavier plate is pressed down beneath the lower-density plate (subduction). This occurs, for example, along the west coast of South America and in the Himalayas. Powerful earthquakes also occur where the plates slide alongside each other, such as in California. Shallower earthquakes that release less energy are common at spreading zones where the lithosphere plates move away from each other, such as at the Mid-Atlantic Ridge, which runs more or less through the middle of the whole Atlantic Ocean (see Fig. 5.1).

Most of the energy-rich earthquakes that account for 95 percent of the energy released by earthquakes occur around the Pacific Rim (known as the Ring of Fire) and along the string of mountain ranges that extends from the Alps via Greece and Turkey to the Himalayas and onward to the southeast, all of which consist of colliding lithosphere plates.

The area where an earthquake is generated, known as the focus or hypocentre of the earthquake, varies in depth from near the surface down to a depth of 680 km, and earthquakes are classified as shallow (<70 km), intermediate (70–300 km) and deep (>300 km) (Kearey and Vine, 1996). All earthquakes in Sweden are shallow.

In addition to being caused by plate tectonic processes, earthquakes can also occur in areas that have been subjected to loading by large quantities of ice or water (causing downward flexure) or unloading (causing rebound and uplift). Sweden has been situated far from active plate boundaries for millions of years. The rock stresses in the Swedish bedrock are caused primarily by pressures from the sea floor spreading zone that extends from north to south along the Mid-Atlantic Ridge (see Fig. 5.1).

Due to this sea floor spreading, the Atlantic is widening at the rate of 2–3 cm/year, causing the bedrock in Sweden to be compressed from a northwest to a west-northwest direction. This “ridge push” generates the maximum rock stress σ1, which is near-horizontal and usually amounts to (normalized) 20–30 megapascals (MPa) (Stephansson et al. 1991). The Swedish bedrock is also affected to a lesser extent by stresses caused by the most recent 3 km thick ice sheet that covered Sweden up until 15,000−9,500 years ago (Lagerbäck and Sundh, 2008).

5.3 Earthquake magnitude

As noted above, an earthquake occurs when the accumulated stress exceeds the strength of the bedrock, causing fractures in the rock or movements (displacement, slip) along existing fracture planes (faults). The released vibration energy, or the magnitude of the earthquake, is proportional to the size of the movement and the area of the fracture plane. Since the stress in the bedrock has to be built up after an earthquake as the stress energy has been released, earthquakes occur episodically, and the number of earthquakes of a given magnitude occurs with a certain regularity. Powerful earthquakes occur less frequently than small ones, and with each increase in magnitude by one the number of earthquakes decreases by roughly a factor of 10.

The most well-known scale for describing the magnitude of an earthquake, and the one most widely used in the media, is the Richter scale, which is equivalent to the more modern M_L scale, where M stands for magnitude and L for local. The Richter scale was created in the 1930s to measure the magnitude of earthquakes with epicentres in California, and the currently used M_L scale is calibrated to the scale of the original instrument (Bödvarsson et al. 2006).

Magnitude according to the Richter scale is quick to calculate, and the magnitude in itself is related to the measured amplitude of surface vibrations and the distance to the epicentre. The scale is logarithmic, which means that the amplitude of the surface vibrations for an earthquake with a magnitude of 5.5 is 10 times higher compared with a 4.5 magnitude earthquake and the energy released is 32 time greater. The Richter scale and the equivalent local magnitude scale are useful for less powerful and shallow earthquakes (<70 km) with an epicentre within a radius of 600 km from the seismic monitoring stations.

The moment magnitude scale, M_W, where M stands for magnitude and W for moment, can also be used to calculate the magnitude of the more powerful earthquakes, above the size where the M_L scale is applicable. The M_W scale corresponds roughly to the total vibration energy released and is the scale that best takes into account the physical mechanism of earthquakes. The M_W magnitude is related to the total movement along a fault surface, the area of the surface along which the movement has occurred and the elastic properties of the rock.[2] As with the M_L scale and the Richter scale, each step up in magnitude is equivalent to 32 times more energy released. M_W magnitudes of less than 2 are usually not noticeable, and material damage does not occur until an M_W greater than 4 (Tarbuck et al. 2011).

5.4 Earthquakes in Sweden

Seismic activity, i.e. surface vibrations caused by earthquakes, is not homogeneously distributed in Sweden but is concentrated to the area around Lake Vänern, the coast of Norrland (the northern half of Sweden) and along the postglacial faults in, above all, the Skellefteå area and northern Norrbotten County.

The earthquakes around Lake Vänern occur in the boundary between two bedrock provinces in southwestern Sweden (between the Eastern segment and the Idefjord terrain) and are considered to be caused by the plate tectonic forces that are causing sea floor spreading at the Atlantic at the Mid-Atlantic Ridge.

Another earthquake cluster is located in southernmost Sweden along the Sorgenfrei-Tornquist Zone, which coincides with a very old lithosphere plate boundary (Söderbäck, 2008). The most recent earthquake in Sweden along the Sorgenfrei-Tornquist Zone occurred in 2012 in the Kattegat, 50 km west of Halmstad, and had a magnitude of 4.1.

The concentration of earthquakes in Norrland has a more complex origin and is probably caused by a combination of plate tectonic forces, faults between areas with differing geology, and the adjustment of the lithosphere to shallower levels after the last ice

[2] http://www.snsn.se/ (downloaded 1 Dec. 2015).

age (isostatic rebound). Postglacial faults occur mainly in the interior of northern Norrland and at a few places further south, as well as in the area near Skellefteå. Most have a NNE extent and follow older fracture zones in the rock that are several kilometres in depth. Their vertical displacement (fault scarp) can be followed for up to hundreds of kilometres and is generally between 1 and 10 metres, but may be greater as at the Laino-Suijavaara Fault, where the vertical displacement is 30 m (Korja and Kosonen, 2014).

In the case of each individual postglacial fault, displacements are considered to be the result of a single earthquake, including any foreshocks and aftershocks, that occurred during, right after and in some cases before the last deglaciation (Lagerbäck and Sundh, 2008). The magnitude of these earthquakes has been estimated at 8 or more (Arvidsson, 1996; Mörner, 2003; Lindblom et al. 2015), while the earthquakes at the postglacial faults that are seismically active today normally have a magnitude less than 4. Together with Lake Vänern, the area around one of these faults (the Burträsk Fault) south of Skellefteå has the highest earthquake frequency of any area in Sweden (Juhlin and Lund, 2011). More than 1,500 earthquakes have been recorded there since 2012, most very small ones (M_L<2), but with a depth of up to 35 km (Lund et al. 2014).

Most natural earthquakes in Sweden have a focus (hypocentre) at a depth of between 7 and 40 km (Korja and Kosonen, 2014). They are normally shallower than about 20 km. The shallowest recorded earthquake of significant magnitude (>2.5) was the Norrtälje earthquake of 1979 (M_L 3), whose focus was only 800 m deep.

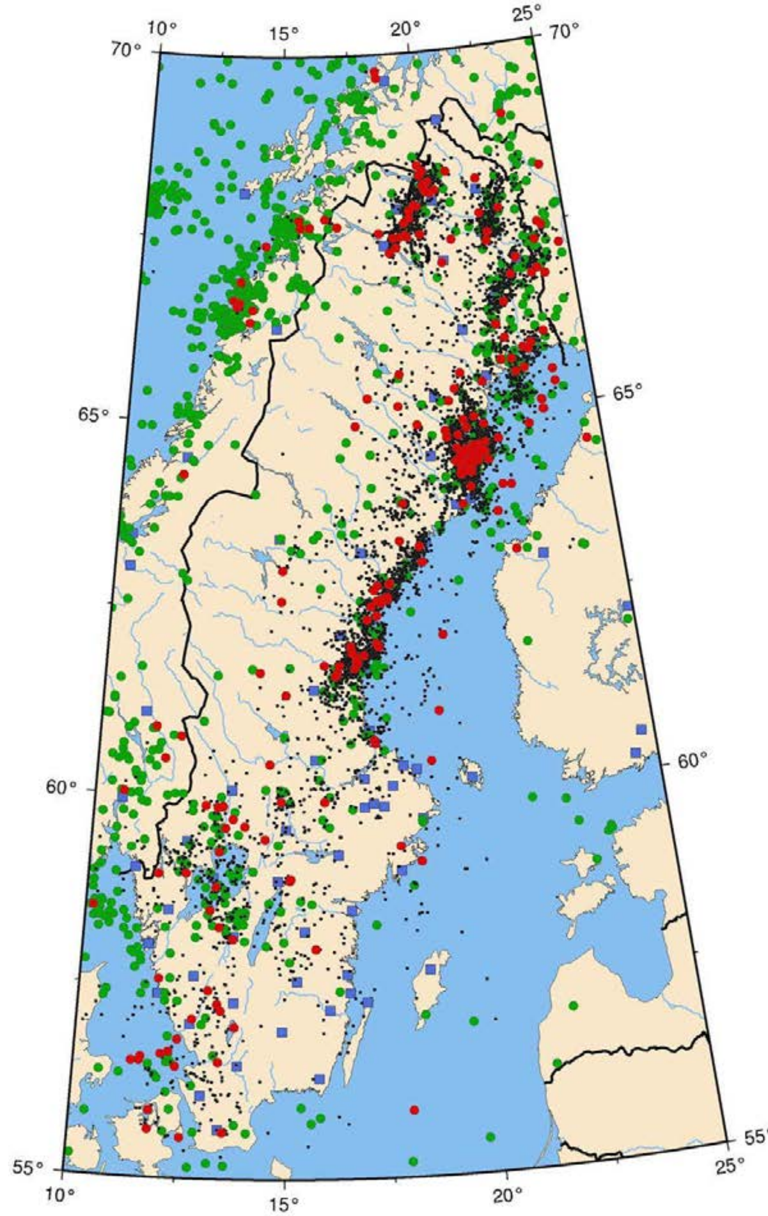
The displacement or slip along a fault that occurs when the elastic strength of the bedrock is exceeded is directly proportional to the magnitude of the earthquake and the area of the surface where the movement has occurred. In the case of earthquakes of magnitude <1, the total slip is less than 1 mm distributed over a radius of maybe 100–200 m, while in the case of a magnitude 5 earthquake the total slip is normally between 0.5 and 50 cm distributed over a fault area with a radius of up to one kilometre (Bödvarsson et al. 2006). This means that the slip per unit area is small and is concentrated to the area around the focus.

Every day the 65 seismic monitoring stations run by SNSN record an average of two natural earthquakes, around eight induced earthquakes caused by subsidence in deep mines, and 20–30 blasts in quarries and on building sites. The mine-induced earthquakes are shallow and local but can be quite powerful. A mine-induced earthquake at Malmberget in the summer of 2015 had a magnitude of 3.5.

The most powerful earthquake recorded in the vicinity of Sweden since seismic instruments were installed is the Oslofjord earthquake in 1904, with an epicentre south of Oslofjord. This earthquake had a magnitude of 5.4 (Bungum et al. 2009). It was thus significantly more powerful than the earthquake of magnitude 4.8 that occurred outside Kaliningrad in 2004 and was clearly felt in large parts of Skåne in the far south of Sweden.[3] Earthquakes of a certain magnitude occur with a certain statistical regularity. Most earthquakes in Sweden have a magnitude of <2.5 and occur relatively frequently. On average, two earthquakes with a magnitude of 3 occur per year, one earthquake with a magnitude of 5 every hundred years and one earthquake with a magnitude of 6 occurs statistically every thousand years (Bödvarsson et al. 2006). Where these earthquakes will occur is difficult to predict, since relatively powerful earthquakes can occur in areas that have been seismically inactive for a long time, such as for example the earthquake in Kaliningrad in 2004. The same is true of the most recent major earthquake in Sweden, which occurred on 15 September 2014. The earthquake occurred at a depth of 12 km just south of Sveg in central Sweden and had a magnitude of 4.1.

[3] http://www.snsn.se/ (downloaded 1 Dec. 2015).

Figure 5.3 Earthquakes in Sweden and its vicinity



Earthquakes with a magnitude of ≥2 in Sweden and its vicinity between 1965 and 2015. Green dots are from the joint Nordic catalogue (FENCAT) 1965–1999, red dots from the Swedish National Seismic Network (SNSN) 2000–2015, and black dots are all earthquakes (SNSN).

Source: Swedish National Seismic Network.

5.5 Conclusion

Earthquakes caused by loading (glaciation) and unloading (deglaciation) of the bedrock by water during and after an ice age are also relevant to a final repository for spent nuclear fuel. In such a 100,000-year perspective, numerical modelling that takes into account both plate tectonic and glacial processes show that 40 earthquakes with a magnitude greater than 7 and 6 with a magnitude of ≥8 can occur in Sweden (SKB, 2011). The large postglacial faults in Norrbotten are clear evidence of the fact that powerful earthquakes occur in conjunction with the retreat of massive continental ice sheets. Even though Sweden has been glaciated several times during the past millions of years, there are no undisputed traces of powerful earthquakes in the Forsmark region (Lagerbäck and Sundh, 2008; Mikko et al., 2015), and the area is seismically inactive even today.[4] Calculations based on the number of recorded earthquakes and their magnitudes show that the frequency of earthquakes with a magnitude of ≥5 within a radius of 5 km is one every 2.4 million years. Since there have been so few earthquakes in the area since seismic instruments were installed, the calculations are scaled down from all earthquakes that have occurred within a 500 km radius to a 10 km circle around Forsmark. This means that there is great uncertainty in the results (Bödvarsson et al. 2006). Another way to calculate the probability of a magnitude ≥5 earthquake is to combine the rock stresses that are built up by plate tectonic and glacial processes within a distance of 1–2 km from long existing faults. In this model, which has been used to calculate the earthquake risk in Forsmark, two earthquakes with a magnitude over five will occur during a period of 1,000,000 years. The fault slip that occurs in connection with an earthquake is proportional to the area of the fault plane, and the shear movement in the rock decreases with the distance from the fault where the earthquake occurred (the primary fault). In the case of an earthquake with a magnitude of 7.5, the respect distance between the faults and the repository is 600 m (Fälth et al. 2010). Thus, to ensure that the shear tolerance of the copper canisters of 5 cm is not exceeded in the event of an M_L 7.5 earthquake, the repository must be built at a greater distance than 600 m from major

[4] http://www.snsn.se/ (downloaded 1 Dec. 2015).

fracture zones and faults where the movement might occur. Small earthquake movements can, however, occur along smaller existing fractures, and in order not to risk the integrity of the copper canisters, deposition holes intersected by fractures will be rejected.

In a 100,000-year perspective it is likely that a new ice age will occur, which means it is not unreasonable to assume that a powerful earthquake will occur in the Forsmark area. Even though there are no certain traces of major earthquakes since the last ice age in this area, it is wise to follow the precautionary principle, since the known postglacial faults occur along old fracture zones. The respect distance of 600 m between the planned nuclear waste repository and the major fracture zones in Forsmark is therefore warranted.

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6 Risks and effects of low doses of radioactivity on man and environment

6.1 Introduction

The purpose of this chapter is to shed light on the risks and health effects to which man and the environment are subjected by exposure to low doses of ionizing radiation, and to describe the knowledge on which risk estimates are based and the uncertainties that exist regarding exposure to low doses and dose rates.

The term “risk” is used in this context to mean the probability of harmful events multiplied by a measure of the consequences or the severity of the harm. The harmful event here is induction of cancer, and the severity is determined by the chances of survival, with or without treatment. These risks are well-known and to some extent quantified, but considerable uncertainties exist regarding e.g. low-dose radiation. However, the risks of radiation are nevertheless better known than the risks of many chemical substances that can also have carcinogenic effects.

Thanks to the fact that there is a quantitative measure of risk, the authorities have, in their directive to the Swedish Nuclear Fuel and Waste Management Co (SKB), been able to specify a limit value for the maximum acceptable risk to be used as a benchmark in the evaluation of the method for the design of a final repository for spent nuclear fuel.

The question of how risks are perceived, managed and communicated in society in a more general sense has previously been dealt with in the Swedish National Council for Nuclear Waste’s report SOU 2007:38 *Nuclear Waste State-of-the-Art Report 2007 – responsibility of current generation, freedom of future generations* and in report 2007:4 *Risk perspective on final disposal of nuclear waste – individual, society and communication*, which is an in-depth report supplementing SOU 2007:38.

In this chapter we intend to describe, thoroughly but concisely, how these radiation risks arise and how great they are for human beings at a given radiation dose. Our natural radiation environment is described, along with what we can learn from the various releases of radionuclides to the environment that have occurred, intentionally or unintentionally, with a focus on the nuclear disaster in Chernobyl and the releases in the southern Ural Mountains.

In order to provide a perspective on the regulatory limit values set for the final repository for spent nuclear fuel, they are compared with the doses obtained from natural radiation sources in our environment. Different scenarios are also discussed regarding the effects on man and environment if the limit values for the final repository were to be exceeded by up to a thousand times.

The uncertainties in the engineered barriers and in the calculations underlying the assessment of the natural barrier are not discussed, however.

6.2 Fundamentals of radiobiology and radiophysics

6.2.1 Types of radiation

Natural radiation and radiation from medical and industrial applications

In our everyday environment, we are surrounded by radiation from different sources and of differing types:

- On the one hand there is **natural** radiation, also called background radiation, originating from the bedrock and the cosmos, to which man has been exposed throughout his evolution.
- On the other hand there is the broad spectrum of radiation types to which we have been exposed during the past century as a result of **medical** and **industrial** applications.

Natural radiation includes both electromagnetic radiation and particle radiation. Electromagnetic radiation includes everything from radio waves, microwaves and visible and ultraviolet light to gamma radiation. The most common types of particle radiation are alpha and beta particles, which are generated by radioactive decay.

The biological effects are determined by the energy imparted by the radiation to the irradiated object. In the case of the lower energies emitted by electromagnetic radiation, the absorbed energy mainly leads to temperature increases, while the higher energies (UV and gamma rays) cause chemical changes in the irradiated material. The visible wavelengths have a unique biological effect via the eye's ability to transform this light into visual impressions.

Ionizing radiation, dose and dose rate

Ionizing radiation

Alpha (α) particles: Helium nuclei, positive charge, have a range in tissue of less than 0.1 mm. Stopped by a sheet of paper.

Beta (β^-) particles: Electrons with a negative charge. There are also positively charged beta particles, called positrons. Beta particles have a range in water of around ten mm. Stopped by Plexiglas.

Gamma radiation (γ): Electromagnetic radiation (photons) deriving from the atomic nucleus. Has long range, lower energies, is stopped by a few mm of lead, while high energies may need a decimetre of lead to be stopped effectively.

X-rays: Electromagnetic radiation that comes from the atom's electron shells or is produced in X-ray tubes. Usually have lower energy than gamma radiation. Their range in tissue is energy-dependent, typically a few millimetres up to a couple of decimetres.

In this section the focus will be on the electromagnetic radiation, also called photon radiation, that has sufficiently high energy to ionize the atom. Depending on its origin, this type of radiation is called gamma radiation (gamma rays) or X-rays. Particle radiation will also be discussed, in particular beta particles (electrons) and alpha particles, of which the latter are preferably emitted by heavy atomic nuclei such as uranium or plutonium. All of these types of radiation are called **ionizing radiation**, which is the type of radiation that causes chemical changes in the irradiated material. This effect will be further examined in section 6.2.2.

The radiation to which we are exposed in the natural environment usually comes from a radionuclide, i.e. a radioactive isotope of an element. Radionuclides are formed in a nuclear reactor either by the fission (splitting) of heavy elements, giving rise to two other elements (fission products), or by the addition of neutrons to the core (activation products). In the latter case we often speak of actinides, the chemical term for a group of heavy elements that are formed when neutrons are added to a uranium nucleus. The fact that an atomic nucleus is radioactive means that it is unstable, i.e. it has a certain probability per unit time of decaying or being transformed into another radionuclide. The greater the probability of decay, the higher the activity, and the shorter the half-life. The activity of a radionuclide is measured in becquerels (Bq), where 1 Bq is equal to one decay (disintegration) per second.

Dose and dose rate are two fundamental concepts relating to the effects of ionizing radiation. Dose describes how much energy is absorbed by the irradiated object, while dose rate defines the relationship between dose and time. The unit of dose is the gray (Gy), which is equivalent to the absorbed energy of 1 joule per kilogram (J/kg), which is a very high dose in the perspective of natural background radiation, where the total dose is usually a few thousandths of a gray (mGy). Dose rates for natural background radiation are usually in the range of mGy/year, equivalent to millionths of a gray, or micrograys, per hour (μGy/h). Medical applications may involve doses of tens of Gy to tumours, which are irradiated with dose rates of Gy/min.

Dose concepts

Absorbed dose: Defined as the amount of energy deposited by ionizing radiation per unit of mass. The unit is the gray (Gy), 1 Gy = 1 J/kg.

Equivalent dose: the absorbed dose multiplied by a weighting factor that takes into account the biological effect of the specific type of radiation. The unit is the sievert, Sv.

Effective dose: The equivalent dose multiplied by a weighting factor that takes into account the sensitivity of the body's different organs to radiation. The unit is the sievert, Sv. Limit values are normally specified in this quantity.

Dose can also be given as **equivalent dose** in the unit sievert (Sv), which then includes an "effect factor" that varies between different types of radiation depending on their biological effect. The effect referred to is the risk that the radiation will induce cancer and is specified using a radiation weighting factor termed w_R. The equivalent dose (H) in sieverts is defined as $H=w_R \times D$, where D is absorbed dose measured in grays.

By calculating the dose in Sv, the doses from different types of radiation sources can be added together and used for risk assessment as regards stochastic effects, for example the risk that low doses of radiation will give rise to cancer. The term "stochastic effects" is explained in greater detail in the following text.

Table 6.1 The radiation weighting factor for different types of radiation (ICRP 1991)

Type of radiation	w_R
Gamma rays and X-rays	1
β radiation (electrons)	1
Neutrons	energy dependence 5–20
Protons	5*
α radiation	20

*In the ICRP's most recent recommendations, w_R for protons has been changed to 2 (ICRP, 2007).

The unit sievert is also used for **effective dose** and then includes a factor that takes into account the dose to individual organs, since the probability of cancer varies between different organs. If exposure is homogeneous, the equivalent dose and the effective dose are identical. In radiation protection contexts when limit values for exposure are determined, and normally when doses from different types of radiation sources are specified, it is the effective dose that is intended.

6.2.2 How radiation affects cells

Cells are affected by ionizing radiation due to the fact that the absorbed energy causes chemical changes in different parts of the cell. These chemical changes are randomly distributed in the cells, and some can occur in the DNA in the cell nucleus and lead to permanent changes in the cell's chromosomes. These changes can affect the function of the cell and even transform the cell into a cancer cell. At high doses (~ 3 Gy), certain types of cells (in the small intestine and the bone marrow) will die, while cells in other organs (e.g. the brain and muscles) can tolerate several times higher doses before cell death occurs.

Cell death that leads to failure of an organ is called a **deterministic** effect and occurs when a threshold dose has been exceeded. At lower doses that do not cause cell death, there is a risk that permanent damage (mutations) will occur in the cell's DNA. Some mutations can eventually cause the cell to become a cancer cell. It is impossible to predict which cell or cells in the irradiated area will be transformed into a cancer cell, so this effect is termed stochastic (random).

In the dose range around 100 mGy and above, radiation damage in cells can be detected as chromosomal damage or mutations. Markers for cellular response have been lacking at the low doses and dose rates that characterize background radiation, but it has been shown by means of molecular biological methods such as analysis of gene and protein expression that cells react at doses as low as 1 mGy and at dose rates of mGy/h. While the traditional markers for genotoxicity are not sensitive enough to observe at doses in the mGy range, molecular biological methods have made it possible to describe which cellular processes are affected at low doses and dose rates.

Cell cultures and studies at the organism level (mice, fish etc.) have also shown that cells and organs can be affected negatively by radiation even if they have not been exposed themselves but are merely close to cells and organs that have received a radiation dose. This effect is called the “bystander effect” or “abscopal effect”. This effect has normally been observed in the form of chromosomal damage or cell death in the unexposed cell population. The “abscopal effect” has sometimes been reported in connection with radiation therapy of tumours, i.e. at very high doses (40–60 Gy), and it has been documented in certain patients that tumours outside the irradiation area shrink or disappear.

DNA damage

DNA damage is a common effect of ionizing radiation. It often causes damage to the bases in the molecule, or a break in one or both strands of the DNA molecule. Since DNA damage occurs at high frequency in cells as a result of normal metabolic processes, the cell has developed different mechanisms to repair damaged DNA.

Base damage and single-strand breaks are by far the most frequent kinds of damage. Both of these types of damage are normally repaired without any loss of information, since the undamaged DNA strand acts as a template for the information to be retained in the damaged strand.

A double-strand break is more difficult to repair. If the repair attempt fails, the damage will be permanent. If the cell survives, the information may be altered, resulting in a mutation. Certain mutations can serve as a step in the cell’s transformation into a tumour cell.

Adaptive response is a form of response that is of interest with regard to effects at low doses. This response has above all been studied in cellular model systems, but has also been observed in some cases in laboratory animals. Adaptive response has been demonstrated when cells are first irradiated with a low dose (10–100 mGy) which is followed after a few hours by a high dose that causes observable effects in the form of chromosomal damage or cell death. The effect is less severe in the cells that have received a low dose prior to the high dose. The primary mechanism that is discussed is that the first low-dose exposure initiates the cell's DNA repair system, and when the cells are exposed a second time the repair functions are optimized. This type of response has been discussed in terms of the fact that low radiation doses could optimize the cells' repair capability and thereby also have a positive effect in protecting against other genotoxic substances in our environment. However, scientific support is lacking to show that radiation-induced adaptive response affects the cancer risk for humans.

6.2.3 Effects on man and the environment

Historic background

Less than a decade after Wilhelm Röntgen's discovery of "Röntgen rays", the first medical applications such as X-ray diagnostics and tumour therapy had been put into use, and the first harmful effects of radiation had been reported in the form of tissue damage. An increased frequency of cancer among radiologists was described in 1907, and in 1917 it was shown that radiation can cause an increased rate of sterility among radiologists. The extensive use of X-ray tubes for different applications created a need to be able to compare and calibrate the equipment, and in the absence of physical measurement instruments a biological dosimetry method was developed involving the "skin erythema dose" where for example the underarm was irradiated and the time needed to cause reddening of the skin was measured. A skin erythema dose could then be calculated for a specific X-ray tube based on distance to the tube and time in the radiation field. A skin erythema dose is equivalent to about 2 Gy in modern units.

The extensive use of X-ray equipment, as well as radioactive isotopes such as radium in medicine and research, made it necessary to introduce safety rules to prevent injuries due to excessive exposure of personnel and patients. The first international radiation protection conference was arranged by Rolf Sievert in 1928 in Stockholm, where the groundwork was laid for the regulatory framework that was subsequently developed by international organizations such as the International Commission on Radiological Protection (ICRP), the United Nations Scientific Committee on Effects of

Atomic Radiation (UNSCEAR) and the International Radiation Protection Association (IRPA). Rolf Sievert was also a pioneer in the development of measurement instruments for determining doses from different kinds of radiation sources, which laid the foundation for a measurement system for exposure.

Research on the mechanisms behind radiation injuries also began at the start of the previous century, and in 1927 the geneticist Herman J. Müller at Columbia University in New York City was able to show that radiation caused mutations in fruit flies, for which he received the Nobel Prize in 1946. The body of evidence indicating that radiation can induce cancer in humans grew as groups of people were exposed to radiation from various sources. A relationship was shown to exist between skeletal cancer and radium in women who painted watch dials with luminous paint containing radium, and increased incidences of cancer were documented during the 20th century in many occupational groups that were exposed to radiation.

Background to present risk estimate

"Life span study" (LSS). Survivors from Hiroshima and Nagasaki.

Research programmes are underway to study the health effects among survivors of the atomic bombs in Hiroshima and Nagasaki. The study includes 94,000 exposed individuals plus a control group of 27,000 that have not received any dose. The 17,000 individuals who are estimated to have received a dose in excess of 100 mSv comprise the most important group for estimating risk, since significantly increased risks can be observed for this group.

The dose to the victims in the two Japanese cities came from external irradiation by photons and neutrons for a very brief instant, fractions of a second. It is known that high dose rate and high dose have a greater biological effect than low dose rates, since the cell does not have time to repair the DNA damage to the necessary extent. The ICRP has therefore introduced a factor, DDREF (Dose and Dose Rate Effectiveness Factor), which is used to correct for this. A DDREF of 2 is currently used, which means that the biological effect is assumed to be twice as great per dose unit at high doses and dose rates as at low ones.

The largest body of evidence for the relationship between dose and risk of different types of cancer has come from the “life span study” of survivors from the atomic bomb blasts at Hiroshima and Nagasaki in 1947, which includes some 120,000 people. The studies are still underway, since some of the exposed individuals are still alive. Large epidemiological studies have also been conducted on workers in the nuclear power industry and on people exposed in connection with nuclear power accidents such as Chernobyl. These types of studies have led to risk estimates for various types of cancer, but also for cardiovascular disease, cognitive impairment and clouding of the eye’s lens. The study of survivors from Hiroshima and Nagasaki has also yielded knowledge regarding genetic damage, even though no statistically proven effects of radiation have been found. The risks to humans will be discussed in greater detail in the following sections.

During the past decade, radiation protection of the environment has also come into focus, and the previous assumption that “if man is adequately protected, so is the environment” has been re-evaluated. The ICRP and a number of other national radiation protection organizations now believe that models for calculating dose to various organisms should be used to provide more reliable information on how different species can be affected by different exposure scenarios. Radiation protection of the environment is intended to protect biotopes so that biodiversity can be preserved, see further description in section 6.4.4.

6.2.4 Medical and industrial applications

The medical applications of ionizing radiation for diagnostics and therapy are extensive and contribute about 2 mSv/y to the average individual dose. The most common type of radiation comprises X-rays, and even though the dose is low the dose rates are very high. Different diagnostic methods such as radiography, computed tomography (CT scan) and positron emission tomography (PET scan) have been developed into invaluable tools for diagnosing various illnesses or traumas (bone fractures and injuries). Radiation therapy (radiotherapy) is used to treat cancer either alone or in combination with surgery/immunotherapy or chemotherapy in nearly 60 percent of all treatments. In the nursing professions there are certain personnel categories that are exposed to ionizing radiation with dose limits that are stipulated by radiation protection regulations.

There are also industrial applications that can give small dose contributions to certain occupational categories, such as technicians in nuclear power plants with certain duties. Other examples of industrial and technical applications are sterilization of medical equipment, quality control of welded pipes, smoke detectors and flue gases analysis instruments in incinerators.

6.3 Natural background radiation

Man has always been exposed to natural background radiation. Background radiation derives either from the cosmos or from naturally occurring radionuclides present in our bodies, in our homes and in the ground. Naturally occurring radionuclides may originate either in the processes that led to the formation of the universe, or from an interaction between cosmic radiation and matter, especially the atmosphere. Examples of the former are ^{238}U and ^{40}K, while ^{14}C is the most common radioactive isotope produced by cosmic radiation.

The natural radiation we are exposed to derives from four sources (Andersson et al. 2007):

- Cosmic radiation, annual dose 0.3 mSv (at sea level).
- External radiation from the Earth's crust, average annual dose in Sweden 0.04 mSv.
- Radiation from natural radionuclides in our bodies, mainly potassium-40, contributes 0.3 mSv annually.
- Naturally occurring radionuclides in the building materials in our homes give a dose of 0.5 mSv/y.

Another contribution is from radon-222, a radioactive inert gas with decay products called radon daughters. Radon is produced in the ground and in building materials by the decay of radium-226. The size of this contribution varies between different locations in the country and different types of homes, but the average value is around 3–4 mSv per year.

6.3.1 Variations in the natural background level

Cosmic radiation (cosmic rays), which consists primarily of particle radiation, contributes about 0.3 mSv per year at sea level, but over 0.4 mSv in the mountains. The atmosphere and the Earth's magnetic field provide important protection against cosmic radiation. If we were exposed to the same radiation levels that exist in outer space, we would soon receive lethal doses.

The contributions made by external radiation from the Earth's crust and by building materials are highly dependent on the composition of these materials, since different minerals and materials contain different concentrations of uranium and thorium. It can be noted that the difference in dose depends on whether one lives in an apartment or a single-family house. The average dose in apartments in Sweden is estimated to be 0.73 mSv/y, while the average dose in single-family houses is 0.39 mSv per year. This is a difference of 0.34 mSv/y, which is more than 20 times the target value for a final repository.

The natural radiation from the bedrock in Sweden varies by a factor of 2. Stockholm County is highest with an average of 0.058 mSv/y and Västerbotten County lowest with 0.031. These values are calculated for people who spend 10 percent of their time outdoors (Andersson et al. 2007). There are also areas in the world with a high natural background radiation, for example India, China and Iran. In these areas, relatively large populations can be exposed to a background radiation level of 5–10 mSv/y, with occasional small "hot spots" with a much higher dose, 50–100 mSv or more, mainly linked to radon exposure.

6.3.2 What can we learn from the natural background radiation about the risks of a final repository for spent nuclear fuel?

The natural background radiation can improve our knowledge in two specific areas:

- Transport of radionuclides from a final repository through the "natural barrier" up to the human environment.
- The risks entailed by chronic exposure to ionizing radiation.

Studies of naturally occurring radionuclides are useful in gaining a better understanding of how radioactive material that has for some reason passed through the engineered barriers surrounding a final repository will behave. The most common radionuclide in the waste, uranium, also occurs widely in nature in trace quantities. Furthermore, since it is primarily the same isotope of uranium, ^{238}U, that is involved in both cases, it is possible, by studying how this isotope and its daughter products move in the ground and biota, to gain knowledge that can serve as a basis for estimating what effects this component of the canister contents can have if it reaches the biosphere.

Regarding the radionuclides that are expected to make the greatest contributions to the absorbed dose if they escape from the encapsulated waste, there is not as much to learn from studies of natural radionuclides. The reason for this is that they are mostly long-lived fission products, which do not occur naturally in any large quantities. Uranium and other actinides that are produced in the fuel cycle are much less mobile in the geosphere and the biosphere, which, when all factors are considered, means that the contribution made by these radionuclides to the dose to man is low in relation to that from the more mobile fission products.

There are a number of regions in the world with very high ground radiation (section 6.3.1), due to the presence of particularly rich deposits of uranium or thorium in the bedrock. The population in these areas has been studied with regard to e.g. cancer epidemiology and frequencies of chromosomal aberrations (Hendry et al. 2009). These studies have not yet been able to find any statistically significant evidence for harmful effects of the higher background radiation. Part of the reason is that there is no reliable data to compare with, such as cancer registries and well-documented dose calculations. This is particularly critical since the health effects are likely to be small, even though they affect relatively large population groups.

6.4 Radiation dose to man and the environment from the final repository for spent nuclear fuel

6.4.1 Regulatory requirements on the final repository

The Swedish Radiation Safety Authority (SSM) has formulated its requirements concerning protection of human health in SSMFS 2008:37, where Section 5 reads:

> A repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk.

It is further stated in the same section that the risk shall be calculated using the probability coefficients provided by ICRP Publication 60, which was published in 1991. By "harmful effects" is meant here cancer, both non-fatal and fatal, as well as hereditary defects, also in accordance with ICRP 60 (ICRP, 1991). The Swedish Radiation Safety Authority also had to take EU legislation into account when formulating requirements on the repository.

ICRP 60 contains the fundamental recommendations from the ICRP. Here the estimated risk of fatal cancer, as an average value for the whole population, is given as 5.0 percent per Sv; the ICRP also includes cancer cases without a fatal outcome. The values are weighted with respect to consequence. The concept of "detriment" is used for this purpose, as a measure of the risk regarded as a *consequence-weighted probability*. With this terminology, the detriment for fatal cancer is 5.0 percent, non-fatal cancer 1.0 percent and severe hereditary defects 1.3 percent per Sv. This adds up to 7.3 percent, which means that the risk requirement set by the regulatory authority corresponds to a maximum dose of 0.014 mSv per year.

In 2007, the ICRP came out with updated and revised fundamental recommendations in ICRP Publication 103 (ICRP, 2007). In the same way as in ICRP 60 they have estimated the detriment, which in this report is 5.5 percent for cancer (including non-fatal) and 0.2 percent for heritable effects per Sv, for a total of 5.7 percent. This is a slightly lower estimated risk, due mainly to new knowledge about heritable effects. The maximum permissible dose calculated using this updated risk is 0.018 mSv per year, compared with 0.014 mSv per year – a difference that must be regarded as insignificant, in view of the uncertainties.

The ICRP has also published a report that directly concerns geological repositories: *Radiological protection in geological disposal of long-lived solid radioactive waste* (ICRP, 2013). This publication specifies an annual recommended dose constraint (limit) of 0.3 mSv to a critical population group (Section 54).

The current general dose limit for the public stipulated by SSM of 1 mSv/y (ICRP, 1991; 2007) refers to the aggregate dose from all radiation sources to which the public may be exposed. In other words, the dose contributions from the individual sources must be lower.

Table 6.2 Examples of doses for different exposures

	Annual dose (mSv)
Maximum permissible dose from the final repository for spent nuclear fuel	0.014
Maximum annual dose limit for the public, general	1
Maximum permissible dose for personnel in radiological occupations	20
Maximum permissible radon concentration in new buildings, 200 Bq/m^3	about 7
Natural average annual background in Sweden, excl. radon	1.1
Average annual dose to the population from medical diagnostics	0.9
Estimated average dose to personnel who work on airplanes	3
Dose from natural carbon-14	0.012

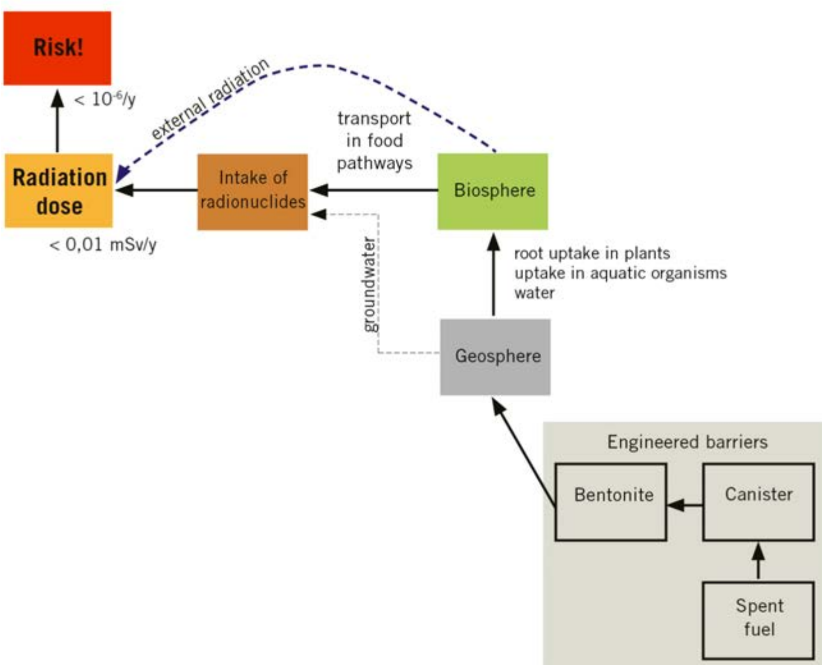
In this context it is important to note that the risks that are estimated from studies of the survivors in Hiroshima and Nagasaki are based on external exposure for a very brief instant, fractions of a second. However, the ICRP has recalculated the risk so that it applies for protracted exposures (see infobox section 6.2.3). The exposure which humans may be subjected to from the final repository is protracted and largely internal, via intake of various radionuclides.

6.4.2 Exposure pathways

A crucial step in the safety assessment for the final repository for spent nuclear fuel is performing and describing an estimation of the radiation dose to humans. Effects of ionizing radiation on the environment shall also be described.

A leakage from the repository that results in exposure of humans to ionizing radiation entails that radionuclides have passed through the engineered barriers and been transported up to the surface with the groundwater. First these radionuclides will be show up in water, which will carry them up to the biosphere. People who live in the affected area may be exposed to these radionuclides, primarily via internal exposure. This occurs first via drinking water and later via locally produced food, such as agricultural products, game and fish. A small, relatively insignificant dose contribution may also occur via external irradiation by radionuclides on the ground surface. There is also a little theoretical possibility that a small part of the exposure may occur via inhalation of radionuclides or gaseous chemical compounds, chiefly ^{14}C in the form of carbon dioxide and radon.

Figure 6.1 Illustration of the flow from deposited spent fuel to cancer risk for humans



Residents in the near-field are exposed to risk, mainly via oral intake of radionuclides that have passed through the barriers and travelled up to the surface. The small contributions that can come from inhalation of radionuclides in the air have been neglected.

A number of food chains can be identified for transferral of radionuclides from biota to man. An example of a common such food chain is grass – cow – milk. This is a relatively efficient way to transfer certain radionuclides to man, particular nuclides of iodine. Cesium, however, is more efficiently transferred via the chain grass – cow – meat, or even more efficiently via lichen – reindeer – meat. An efficient food chain is characterized by efficient root uptake and expensive uptake in the gastrointestinal tract of both animals that people eat and humans. Furthermore, the nuclide that is taken up in animals should then be concentrated in the parts that people eat. Many heavy actinides exhibit not only low root uptake, but very little uptake from the gastrointestinal tract. Moreover, the radionuclides of e.g. plutonium that have entered the body of an animal have a tendency to be concentrated in the skeleton, making them less available via food.

In the case of internal exposure, the absorbed dose is determined by the uptake and retention of the radionuclide in the body. The ICRP has developed biokinetic models for virtually all radionuclides. This also includes data on the uptake (ICRP 2012; 2015) that serves as a basis for the calculation of the dose factors (coefficients), expressed in Sv per unit of activity intake. These data are primarily intended to be used in situations involving occupational exposure of individuals to different radionuclides. In the case of oral intake via food or drinking water, the fraction of activity intake that is taken up in the blood from the gastrointestinal tract is of great importance. The radionuclide composition of the activity that reaches the surface and thereby becomes available to man is affected by how mobile a nuclide is, and to what degree it dissolves in water. So even if a large fraction of the activity in the final repository derives from heavy long-lived radionuclides, it is nevertheless the fission products that make the greatest contribution to the dose to man.

6.4.3 Exposure scenarios if the engineered barriers fail

The transport of radionuclides in the geosphere and the biosphere is controlled by the chemical properties of the different nuclides, such as solubility in water, uptake in plants via roots, etc. In order to analyze different scenarios, knowledge of the different radionuclide-specific transport parameters is therefore needed. Based on transport models, SKB has calculated how the annual effective dose will be dependent on time after repository closure.

As long as the engineered barriers (including the copper canisters) remain intact, the dose (above background) to people living in the area will be zero, since no radionuclides will leak out. The primary function of the repository system is to isolate the waste, while its secondary function is to retard transport to the surface. SKB has also calculated the dose to a population on the surface near the final repository in a number of cases with different types of defects in canisters or buffer caused by e.g. corrosion or earthquakes. These scenarios of different probabilities from “probable” to “hypothetical” are presented in the report SR-Site (SKB, 2010).

The radionuclides that will contribute to the internal dose to individuals on the surface in the event of a leakage will vary with the time after closure:

- Very early leakage, less than about 100 years after closure. Cesium-137 and ^{90}Sr may be of limited importance, aside from ^{14}C and ^{129}I.
- Leakage that occurs roughly 1,000 years after closure. Carbon-14, but also the long-lived fission products ^{129}I and ^{79}Se, under certain circumstances, as well as ^{108m}Ag.
- A leakage after 10,000 years leads to radiation doses primarily from ^{129}I and other long-lived fission products, ^{79}Se and ^{59}Ni. But there is still a significant contribution from ^{14}C.
- In the case of a leakage that occurs after 100,000 years, most of the dose will come from ^{226}Ra. This isotope is not initially present in the waste, but is a decay product of ^{238}U and will increase very slowly, since ^{238}U is the main constituent in the spent fuel. ^{129}I and ^{237}Np still contribute to the dose as well.

The above can be regarded as examples. It is above all radionuclides that are mobile in the bedrock (i.e. dissolve in water and have a low tendency to bind to particles) that contribute to the dose. This is why e.g. plutonium isotopes, as well as certain fission products such as ^{99}Tc, are absent from the above list.

Probabilities of different scenarios depending on the reliability of the barriers are not discussed in this chapter, nor is uncertainty in the parameters that affect the efficiency of the natural barrier. In all the scenarios that SKB does not judge to be improbable, the total result of these calculations is that the absorbed dose to nearby residents falls short of the stipulated maximum value by a good margin. We can, however, note that according to SKB's calculations, the resulting dose in some "hypothetical" cases will exceed the set limit value.

In a hypothetical scenario where 1,000 people reside and earn their living near the final repository and may thereby be exposed to radiation from leaking radionuclides during their lifetime, the following cancer-related negative health effects can be expected. For the sake of comparison, the estimated risk over a period of 100 years is also given, since this is roughly equivalent to a human lifetime:

- *No leakage from the final repository.* Assuming the same "natural" risk of dying of cancer as the average Swede has today, some 200 people will die of cancer not caused by radiation.
- *10 times the dose limit.* This is equivalent to 10 percent of the background radiation. A risk of 1 in 100,000 leads to an additional 0.01 cancer death every year. This amounts to about 1 extra cancer death in 100 years, compared with the expected 200. Advanced equipment is needed to detect an increase in radiation of 10 percent of the background radiation from the radionuclides.
- *100 times the dose limit.* Same as the background radiation. A risk of 1 in 10,000 means 0.1 expected cancer death per year. The cancer cases increase by a total of 10, but are still within the statistical margins of error. If this occurs within a few hundred years, it is possible to detect ^{137}Cs with advanced equipment on the site. After this length of time, advanced analysis is still required to detect the radionuclides.
- *1,000 times the dose limit.* A dose that is about 10 times the background radiation leads to an annual risk of 1 in 100. Over a 100-year period, this may mean up to 100 additional cancer deaths. Depending on how long after closure the leakage occurs, it may still be difficult to detect it, but if it occurs within a few hundred years it will be detectable by means of simple measurements on

the site. It is, however, uncertain whether an epidemiological study of only 1,000 individuals will enable these consequences to be observed, since there are so few exposed individuals. According to SKB's calculations, these doses and risks will be reached if all the canisters have a large initial defect at the same time as the buffer is lost. SKB regards this as a theoretical case which they have included to ascertain what role the bedrock plays as a barrier.

6.4.4 Radiation protection of the environment

The first section of the Radiation Protection Act from 1988 (SFS 1988:220) reads: "The purpose of this Act is to protect people, animals and the environment against harmful effects of radiation."

For a long time it was thought that if the regulations ensure that man is protected, then the environment and animals will also automatically be protected, since man is more sensitive to radiation. This view has been questioned in recent years, however, and the most recent recommendations from the International Commission on Radiological Protection (ICRP), published in ICRP Publication 103 (2007), raised the question of developing a regulatory framework for radiation protection of biota in a broader sense. It was pointed out that this is a very complex question, since it is difficult to formulate in regulations what is to be protected and what effects are to be protected against. These questions must therefore be identified and defined in the continued work.

The effects on biota, just like the effects on man, are caused by the fact that ionizing radiation damages the cells, mainly DNA, but other cell functions can also be affected. When it comes to protecting the environment against harmful effects of radiation, "tumour induction" is not the primary concern for organisms other than man. Instead it is harm to the ability to reproduce that is one of the critical effects, aside from survival. In effect, one might say that it is biodiversity we are seeking to preserve.

The impact on the environment of higher radiation doses can be defined by saying that the organisms that occur naturally in a biotope are affected in such a way that they can no longer adapt to live in this environment. As a basis for a regulatory framework for radiation protection of the environment, the ICRP has, in Publication 108 (2008), identified and proposed a definition of what is meant in this context by “deleterious effects”. Beyond this, the ICRP has also identified and proposed a number of reference organisms representing flora and fauna. Further studies of radiation sensitivity and dosimetry will be conducted for these organisms. The effects which the ICRP has chosen to focus on in developing a terminology and a system for radiation protection of the environment (e.g. non-human organisms) are (ICRP 2008):

- Mortality, early death of the organism could lead to changes in age distribution and population density.
- Morbidity, some morbid changes could reduce the fitness of individuals, making it more difficult for them to survive in a natural environment.
- Reduced reproductive success.
- Chromosomal damage, mutations.

Organisms chosen as reference organisms represent different ecological niches:

- Large terrestrial mammals – Deer
- Small terrestrial mammals – Rat
- Aquatic birds – Duck
- Amphibians – Frog
- Freshwater fish – Trout
- Marine fish – Flatfish
- Terrestrial insects – Bee
- Marine crustaceans – Crab
- Terrestrial annelids – Earthworm
- Large terrestrial plants – Pine tree
- Small terrestrial plants – Grass
- Seaweeds – Brown seaweed

Geras'kin et al. (2008) have studied how non-human organisms have been affected by radiation in the vicinity of Chernobyl. At the lowest dose rates, around 50 mGy per year, genetic effects have been recorded, i.e. permanent changes in DNA, in conifers and mammals. Based on different studies, the IAEA has also concluded that doses < 500 mGy/y can be regarded as safe for animals and < 3,650 mGy/y as safe for terrestrial plants.

The ICRP has stipulated "Derived Consideration Reference Levels" (DCRLs) for different reference animals and plants. DCRLs are dose rate intervals within which there is probably some kind of deleterious effect of radiation for the reference organism in question. Based on the scientific literature, the ICRP has also arrived as dose conversion factors for the different reference organisms (ICRP, 2014). Unfortunately, however, very little relevant data is available on how chronic exposure at a low dose and a low dose rate, i.e. lower than 0.1–1 mGy/d, affects organisms. Effects have only been observed for the reference mammals (deer and rat) when they have been exposed to this dose rate for an extended time. For other organisms, it has therefore been decided to determine at what dose levels it has been possible to observe "acute" severe injuries and then set the DCRL a thousand times lower. The DCRL is then around 0.1–1 mGy/d, which is about 40−400 times as much as the dose limit for the public of 1 mGy/y.

6.5 What have we learned from releases of radionuclides in the environment?

Differences between accidents and releases compared with leakage from a final repository

During the course of history, radionuclides have been released into the environment as a result of human activities. These releases due to accidents, inadequate protection or intentional actions such as nuclear weapons tests have been used to study the cycling of radionuclides in man and the environment and the risks posed by radiation to humans, plants and animals. In some cases, which are described below, the release has caused such high radiation doses to man or the environment that they have led to detectable harmful effects.

Virtually all of these releases have led to the dispersal of radionuclides in the atmosphere, on the ground, or in lakes, rivers or seas. This differs from a leakage from a final repository for spent nuclear fuel, where the source is approximately 500 m down in the rock. Underground nuclear weapons tests can also leak, but the conditions differ greatly from those in the final repository. The difference between transport of radionuclides via groundwater and atmospheric dispersal and deposition is of crucial importance for human exposure in two respects. In the case of fallout from nuclear weapons or releases from a nuclear power plant, intake via inhalation will initially be of relatively great importance. In addition, the deposition of radionuclides on the surface of the ground will initially lead to considerable external exposure, provided that the radionuclide emits gamma radiation. Radionuclides that enter the biosphere from above via dry or wet deposition will find an effective gateway into the food chain via the green plant parts, where the stomata in the leaves serve as a "portal" into the inside of the plant. This is normally a much more efficient uptake than root uptake.

Another, quite significant difference is that releases coming from the final repository have aged considerably, which means that the radionuclide composition will differ from that of deposition/fallout from nuclear weapons tests or accidents. In the case of accidents at nuclear power plants, the radionuclide composition reflects how long the fuel has been used. It can particularly be noted that some of the nuclides that have contributed to the largest dose from the fallout will be absent to a great extent if the source of the release is the final repository, since they will have decayed. For example, no ^{131}I will be left, since with a half-life of only 8 days it will have disappeared even before the fuel is removed from the interim storage pools. The most important isotopes in the fallout from nuclear weapons as well as from the Chernobyl accident, ^{137}Cs- and ^{90}Sr, both with a half-life of about 30 years, will have declined greatly, even though they may still be of some importance due to a high initial activity. Long-lived nuclides, which are sometimes present in the releases that have been studied, normally have a much lower activity due to their long half-lives and have therefore often been overlooked in the studies. Knowledge of the environmental transport of these isotopes may instead often be based on what is known about their stable equivalents.

Table 6.3 Comparison of exposure pathways between leaking repository and deposition of radionuclides from radioactive fallout

After leakage from geological repository	Fallout from nuclear weapons tests or accident
Radionuclides can only enter plants via root uptake.	Uptake via stomata is usually the most important uptake pathway for fallout on green plants. Much more efficient than root uptake.
No, or insignificant, presence of radionuclides on the surface of green plants	Radionuclides can enter the food chain by deposition on the surface of green plants that are eaten by animals or humans.
Negligible dose via inhalation	The inhalation dose can be considerable under certain conditions. This is of greatest importance for nuclides that can only be taken up from the gastrointestinal tract to a very small extent, e.g. plutonium.
External irradiation from the uppermost soil layer is of almost no importance, since radiation from the radionuclides is attenuated in the soil.	External irradiation is of great importance initially, before the radionuclides have penetrated into the soil.
Mainly long-lived radionuclides, $T_{½} > 100$ years, will eventually be able to make a significant dose contribution.	Short-lived and medium-short-lived radionuclides are of the greatest importance.
Groundwater can be an important dose contributor.	Surface water sources can contribute more to the radiation dose than groundwater.

6.5.1 Nuclear weapons testing

The atmospheric nuclear weapons tests carried out by the great powers in the 1950s and '60s resulted in global fallout of relatively short-lived fission products. Studies of the cycling of these nuclides in the natural environment served as a basis for the calculations of their mobility in biota and uptake in the food chains that lead to man.

Through the tests conducted on the Semipalatinsk Test Site in the Soviet Union during the late 1940s and early '50s, relatively large groups of people in the local population were exposed to doses of up to 1,000 mSv or more. So far only a very small number of epidemiological studies have been conducted in the area, but data indicate a slightly greater risk than for the atomic bomb survivors in Hiroshima and Nagasaki (Bauer et al. 2005).

6.5.2 Chernobyl

The nuclear accident in Chernobyl in 1986 led to an extensive dispersal of radionuclides, which were deposited over large parts of Europe. As a result of radioactively contaminated soil in the former Soviet Union, approximately 5 million people were exposed to radiation doses that greatly exceeded the dose from natural background radiation.

It has been estimated that the more than 5 million people who live within the most contaminated area (> 37 kBq/m^2) were exposed to an average dose of 10 mSv over a period of 20 years.

Extensive international studies of effects on man and biota in these contaminated areas have yielded important knowledge concerning the effects of the radiation.

The fallout from Chernobyl was dominated by the more volatile nuclides in the reactor (fission products with relatively short half-lives), which therefore rose higher in the atmosphere during the fire. The dominant contributors to the exposure varied over time. First it was short-lived iodine isotopes, in particular ^{131}I, which, via the food chain grass – cow – milk, contributed relatively high doses to the thyroid gland, particularly in children (since they consume the most milk). This resulted in an increased frequency of thyroid cancer in children in the nearby area who were younger than 18 years when the accident occurred. What is notable about these cancer cases is that they began to appear only 4–5 years after the accident, which was earlier than expected (UNSCEAR, 2000).

In conjunction with the clean-up of the nuclear power plant after the accident, some 200,000 workers were exposed to high radiation doses. As expected, epidemiological studies of this group show an elevated risk of leukaemia (UNSCEAR, 2000).

A month or so after the accident, the external doses were dominated by the radiation from a number of fission products, followed by internal dose contributions from ^{137}Cs. This isotope is also the one whose cycling in the biosphere is being studied most intensively.

^{137}Cs, which has a half-life of 30 years, occurs in sufficiently large quantities to be of interest even when due to leakage from an underground repository, if it occurs at a very early stage. In this case, however, its availability to biota will be lower than when due to atmospheric fallout, since then the radionuclide must be taken up by the plants via their roots.

6.5.3 Mayak

Mayak, in Ozyork in the southern Ural mountains, is a facility where the Soviet Union produced its nuclear weapons. From 1948 and for several years afterwards, considerable quantities of radionuclides were released (usually deliberately) to the atmosphere (at low altitude) and, above all, to the Techa River, which is a tributary of the Ob. This is described in a report from the Norwegian Radiation Protection Authority (Strandring et al. 2008). As a result of these releases, people living near the river had to be evacuated because they had received excessively high radiation doses. The radiation doses received by evacuees were estimated to be up to 1,700 mSv.

When a thermal explosion occurred in 1957 in a waste tank in the Mayak area, this led to further radioactive contamination in the surrounding area.

Epidemiological studies report significant effects in the form of leukaemia and solid tumours. In particular, ^{90}Sr in the drinking water in the area around the river has contributed to the many leukaemia cases. Studies of more than 20,000 internally contaminated persons have yielded a better understanding of how strontium-90 is metabolized in the body. The risk of cancer after this type of exposure has been found to be slightly lower than but still comparable to the estimated risk obtained from studies of the survivors of Hiroshima and Nagasaki.

6.5.4 Fukushima

Considerable radionuclide releases occurred to the air and sea following the nuclear power plant accident in Fukushima in 2011. It is still too early to expect effects in the form of increased cancer frequency in the area. However, it is estimated that about 250,000 individuals were exposed to external doses exceeding 1 mSv, in addition to internal doses (Yamashita, 2014).

6.5.5 Others

Others releases include plutonium from e.g. satellites that have burned up in the atmosphere or crashed onto the surface of the Earth, such as SNAP-9A, which burned up in 1964 above Madagascar and which contained 630 TBq of alpha-emitting ^{238}Pu (Hardy, 1973). Other events include aircraft armed with nuclear warheads that have crashed, which occurred in Palomares, Spain in 1966 and on the ice off Thule on Greenland in 1968. None of the accidents have led to measurable harmful effects on humans or the environment, but they have made it possible to study how plutonium disperses both in the sea and on land. Moreover, measurements of plutonium uptake in humans have provided knowledge on how the nuclide is taken up and metabolized in the body.

Table 6. 4 Releases in the environment

What?	Noted
Nuclear weapons detonations in the atmosphere. Local contamination.	Certain places with considerable fallout of short-lived radionuclides: **Semipalatinsk** – High doses to local population, epidemiological studies ongoing. **Nevada** – Military personnel were exposed to irradiation; some excess mortality in leukaemia has been demonstrated. **The Marshal Islands** in the Pacific Ocean – civilians were exposed to heavy fallout of ^{131}I. **Maralinga** – in southern Australia. British nuclear weapons tests in the '50s. Also mechanical detonations of atomic bombs, resulting in plutonium fragments. Aboriginal population in the area, who found fragments, were exposed.
Nuclear weapons detonations in the atmosphere. Global contamination.	Has provided opportunities for studying transport and cycling of radionuclides in the biosphere: • Root uptake in plants. • Transport with surface water. • Transport in food chains. In this case, the dominant pathway into plants is deposition directly on green plant parts and then into the plant via the stomata.
Windscale 1957. Fire in military graphite-moderated reactor.	Above all ^{131}I released in the immediate vicinity. In addition, the reprocessing plant has released large quantities of ^{137}Cs into the sea (the Irish Sea). This has been traced for a long time in the North Atlantic and adjacent seas.
Mayak 1957. • Releases in the Techa River 1949–1956. • Thermal explosion in waste tank. • Dispersal of activity from dried-up lake.	Facility for production of nuclear weapons in the Soviet Union. Opportunities to study: • effect of chronically low radiation doses to the population • effect of high radiation doses to vegetation • kinetics of chronic intake of ^{90}Sr. Above all ^{90}Sr and ^{137}Cs.
Chernobyl 1986. Releases of large quantities of radionuclides via the atmosphere above large parts of Europe.	**Near-field:** Thyroid cancer in children due to intake of ^{131}I via the chain grass – cow – milk. The cancer cases appeared earlier, and at a higher frequency than expected. Radiation damage to biota. **Sweden:** New knowledge of cycling of ^{137}Cs in forest and game. Transfer pathways to man of ^{137}Cs via different food chains (SSI, 2006).
Fukushima 2011.	Evaluation of effects on humans ongoing. Aggregate releases add up to about 1/10 of the amounts of radioactivity released from Chernobyl.
Goiania, Brazil 1987.	Scrapped ^{137}Cs radiation source was stolen from an abandoned hospital site and caused acute radiation damage to a large number of individuals.
Small releases around nuclear installations in the USA and Canada.	Have provided information on how radionuclides move in biota, especially when released into rivers, e.g. the Columbia River in Washington, where Hanford Laboratories had released significant quantities of different radionuclides.

6.6 Perspectives in time on the risk to man

Will the radiation sensitivity of man and biota change over time?

The risk estimate and the safety assessment are based on knowledge gained during the last 50 years. In order for the risk estimate to be valid over a timespan of 100,000 years, it must be assumed that the radiation sensitivity of man and biota will not change significantly during this span of time.

The first question that needs to be examined is how the next 100,000 years of human evolution will affect the radiation sensitivity of man and biota. The scenario that needs to be evaluated is whether evolution might lead to increased radiation sensitivity. A prerequisite for human evolution is that our genetic material can change, i.e. that the cell's mechanisms for repairing genetic damage are not perfect, so that chromosomal changes (mutations) occur continuously, which, through the process of natural selection, enables species to adapt to changes in the environment which would otherwise threaten their survival (Darwin's *On the Origin of Species* from 1859). This "imperfection" in the cell's repair capability is thus a prerequisite for evolution, but at the same time has a price for the individual since it is the main mechanism of ageing and age-related diseases such as cancer.

Evolution that would make a large part of the population more sensitive to radiation would probably result in earlier onset of cancer and other age-related diseases and lead to a higher risk of detrimental genetic changes. Such an evolutionary outcome ought to be counteracted by natural selection. 100,000 years is a relatively short span of time from an evolutionary perspective, however, and genetic analyses of our forebears who lived tens of thousands of years ago show small changes compared with present-day humans, even though the human habitat has changed drastically.

The second question concerns whether human living conditions could change in such a way that people's radiation sensitivity is affected. In an environment where the risk of cancer and other age-related diseases is increasing, the effects of radiation can lead to an earlier onset of these diseases. Other factors such as technology, medical science and social structure in 100,000 years are also of crucial importance.

6.7 Uncertainties in risk assessment

Uncertainties in risk assessment for low radiation doses and dose rates may relate to the risk of cancer, cardiovascular disease etc. and can be discussed in the light of scientific findings describing the shape of the dose-response curve for different dose rates and radiation types, but they may also relate to whether current radiation protection rules provide adequate protection for man and the environment. Regarding the linear no-threshold (LNT) model used to calculate the risk of cancer in the low-dose range, there is extensive support in the research community suggesting that the model does not underestimate the risk in a way that jeopardizes the health of exposed populations. Based on large epidemiological studies conducted on tens of thousands of people, uncertainty in risk assessment for the dose range 20–100 mSv cannot be greater than a factor of 2. In the dose range 1–10 mSv, uncertainty is greater but probably less than a factor of 5. According to available statistics, between 15,300 and 20,700 (average 18,000) of every 100,000 persons in Sweden will die of cancer. If the radiation risk were increased by a factor of 5, the number of cancer cases in a population of 100,000 people exposed to 10 mSv of radiation would increase from 50 cases to 250 cases, from an expected level of 18,050 to 18,250. When it comes to rules for protection of humans from exposure to chemicals via releases or food, comparable precision does not exist in the risk assessment, and for chemicals with expected genotoxic properties the LNT model comprises the standard for risk assessments.

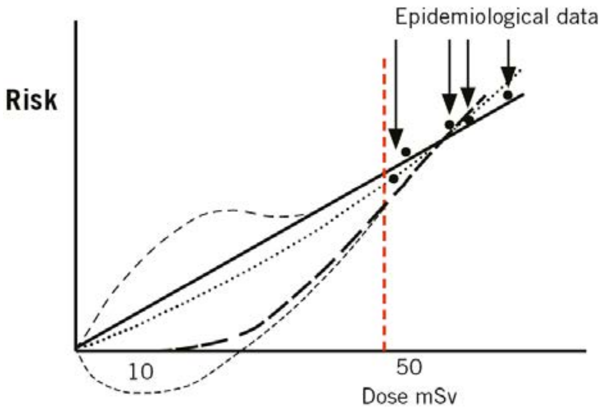
From a scientific viewpoint it is important to understand the effect of low doses and dose rates and different types of radiation on cells and organs. If research can describe how different structures in the cell are affected and which processes are initiated, this may give us a mechanistic understanding of radiation-induced processes in cells and organs and whether these processes are related to protective functions and general stress response, and whether there are threshold doses and dose rates below which cellular responses are lacking or different. The results of this research may then provide new evidence for or against the LNT model.

Six questions that have been the focus of the last 30 years of international research and are still high-priority questions in

Euratom's programme for radiation protection research are listed below:

1. What does the dose-response relationship look like for cancer risk at doses below 50 mSv and at dose rates < 10 mSv/h? (See Fig. 6.2).
2. What does the dose-response curve look like for cardiovascular disease, cognitive ability and damage to the eye's lens at doses below 100 mSv and at low dose rates?
3. What risk model best describes genetic effects on man?
4. How big a difference in radiation risk exists at the individual level?
5. How is the risk affected by exposure to other types of radiation than photons?
6. How is the risk assessment affected by internal irradiation?

Figure 6.2 Different models for the shape of the dose-response curve for cancer risk



- - - - - - Risk higher compared with today's risk assessment
——— Linear extrapolation from high doses, used currently for risk assessment
·············· Risk slightly lower compared with today's risk assessment
— — — Threshold dose below which there is no risk of cancer
--------- Low radiation doses protect against cancer (the part of the curve under the x-axis)

The linear dose-response curve for cancer at doses below 50 mSv that is used in radiation protection to estimate risk is, as discussed above, are not based on scientific results but on the hypothesis that the risk can be linearly extrapolated (LNT) from the higher doses for which reliable epidemiological data exist. Epidemiological studies are the most powerful tool for assessing risk when they are based on studies of very large groups of people, with a good knowledge of dosimetry and with long-term monitoring of health effects. Such studies also include effects of lifestyle, individual sensitivity and other factors that can affect the cancer risk. The resolution of epidemiological cancer surveys is limited by the background level of cancer that normally exists in the population, and since about 35 percent of a normal population will contract cancer it is very difficult to distinguish increases of tenths of a percent in cancer incidence that may have been caused by radiation in the mSv range. At a dose of 5 mSv to a population of 100,000 people, the LNT-based risk estimate gives an increase of 25 cases of lethal cancer, i.e. an increase from 18,000 to 18,025 cases. This is impossible to verify by epidemiological methods, which means that none of the different shapes of the dose response curve in Fig. 6.2 can be ruled out. Some relevant strategies for filling these knowledge gaps will be described below.

6.8 The research front

Several European initiatives have been launched to identify and prioritize research topics of importance for risk assessment regarding effects of low doses and dose rates. An overall strategy is described in a report published in 2009 entitled "High level and expert group. European low dose risk research, Radiation protection".[1] Furthermore, a "Network of excellence" was started within DoReMi 2010 with support from Euratom, followed by OPERRA and in 2015 by CONCERT. These programmes define strategic research agendas which have been implemented in the research programmes supported

[1] https://ec.europa.eu/research/energy/pdf/hleg_report_-_january_2009.pdf (downloaded 1 Dec. 2015).

by FP7 in the EU and for which grant applications are now being received for within the framework of Horizon 2020.

The six questions described in the section above provide a brief summary of the prioritized research programmes concerning radiation safety being funded by Euratom.

The report from 2009 states that the knowledge gaps identified for the low-dose range cannot be filled by traditional epidemiology, which is not sensitive enough, but that the focus is instead on utilizing "modern biology" to obtain a mechanistic understanding which of the dose-response models shown in Fig. 6.2 that are supported by the research. By "modern biology" is meant e.g. studying gene expression and protein expression in cells and the resulting functional responses, for example DNA repair. New research results have shown that the gene and/or protein expression of cells is affected by doses in the mGy range and that changes in these expressions often have a dose-response relationship with threshold values.

The research front for **dose-response relationships in the low-dose range** thus also includes a survey of which cellular functions are affected by low doses, both in order to obtain a mechanistic understanding and to identify biomarkers that can be used to increase precision in epidemiological studies, as reflected in the term "molecular epidemiology". Examples of such biomarkers are markers that can show that a person has been exposed to ionizing radiation, biomarkers that can be used to estimate dose and biomarkers that can show whether a cancer has been caused by radiation. Recently, studies of children exposed to ^{131}I from Chernobyl have identified a biomarker showing that their thyroid cancer is radiation-induced.

When it comes to the risk of **cardiovascular disease,** long-term studies of the survivors from Hiroshima and Nagasaki have shown that there is a statistically significant increase at doses above 500 mSv. Knowledge regarding how the development of these diseases is affected by radiation and what the dose-response curve looks like below 500 mSv is limited, and it is hoped that mechanistic studies in different model systems such as cell cultures and studies of mice will be able to yield greater knowledge of relationships between radiation and cardiovascular disease.

The risk of **genetic effects** of radiation is primarily estimated from studies of mice, and uncertainty exists as to what extent these risks are directly applicable to man. New, powerful tools for analysis of mutations in the human genome (such as Next-Generation Sequencing) offer ways to shed light on whether radiation-induced mutations in gametes lead to an increased risk of heritable genetic changes and to determine correlations with dose, dose rate and radiation type.

Individual radiation sensitivity has above all been of interest in conjunction with radiotherapy treatment of cancer.

Radiotherapy, together with surgery, is the most common form of cancer treatment, and some 35,000 Swedes are diagnosed with cancer every year. Most of the patients that receive radiotherapy suffer small or no side-effects from the treatment. However, a few exhibit acute or delayed side-effects in organs exposed to the radiation field, such as skin damage or changes in the lung or heart due to breast cancer treatment, or in the intestine or bladder due to radiotherapy treatment of prostate cancer or gynaecological cancer. Research aimed at studying the mechanisms behind individual radiation sensitivity has several purposes. One is to develop diagnostic methods to identify patients who are particularly radiation-sensitive, which would make it possible to give normally sensitive patients a higher dose and achieve better tumour control. Another is to investigate the important question of whether individual radiation sensitivity is also manifested at low doses and dose rates, and whether a fraction of the population has a higher risk of developing cancer than has been predicted by the LNT model.

Previous research has shown that certain genetic syndromes that affect genes involved in DNA repair or damage signalling render the bearers of these mutations highly radiation-sensitive. However, such changes are unusual among people classified as radiation-sensitive after radiation therapy, so the research is now focused on identifying genetic changes that do not lead to loss of important functions, for example different forms of DNA repair, but rather reduce their precision and thereby increase the risk that radiation damage will not be correctly repaired. Many genes have functions involved in repair, and research has been initiated aimed at determining whether radiation sensitivity is associated with the interaction of several genes with reduced functionality.

The two remaining prioritized research questions concern risk assessment of low doses and dose rates when it comes to **other types of radiation than photons**, and uncertainties in risk if the radiation dose comes from unstable nuclides that have been inhaled or ingested. In these areas, epidemiological studies comprise an important source of knowledge, and it is believed that development of molecular biological methods can make important contributions to risk estimation after exposure in the low dose and low dose rate range.

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7 Strategies for monitoring programmes in planned final repositories

7.1 Background

The Swedish National Council for Nuclear Waste's state-of-the-art report from 2015 entitled *Nuclear Waste State-of-the-Art Report 2015: Safeguards, record-keeping and financing for increased safety* (Nuclear Waste State-of-the-Art Report 2015) discussed programmes for monitoring in sealed areas. The purpose was to: "shed light on how the issue of monitoring programmes in sealed areas is being dealt with in Europe outside of Sweden, particularly in terms of technology and strategy development." The focus in the report was on international efforts to develop new monitoring techniques and plans for technical installations in sealed areas to monitor the state of the engineered barriers and the rock in the excavation-damaged zone[1]. The following account follows up the chapter in the state-of-the-art report from 2015, but with a broader focus on *strategies* for monitoring.

The purpose of the follow-up is to learn more about the use of results from monitoring programmes from completed and planned EU projects and national final disposal programmes.

Important questions are why monitoring in sealed areas is considered necessary, the design principles for such programmes, and how the results can be used, but also how conflicts with regulations governing long-term safety can be avoided. The point of departure for the discussions is completed and planned EU projects, but study

[1] Excavation Disturbed/Damaged Zone (EDZ) refers to the part of the rock that has been damaged by blasting, drilling and other excavation processes.

visits have also been made to Posiva's demonstration repository in Finland, and the plans for a monitored final repository in Switzerland have been studied.

A central strategic question concerns the purpose of a monitoring programmes for sealed areas: what problems can the programme solve that cannot be solved more simply and cheaply by measurements in easily accessible areas? The table in Figure 7.1 shows that most of the tasks for a monitoring programme can be solved by measurements in open and accessible areas. This is true, for example, when it comes to monitoring of the external and internal environment, feedback to the continuous characterization and modelling of the rock with possible modifications of the repository design, and most verifications that the design premises are fulfilled.

One of the main reasons for monitoring of the performance of the engineered barriers and the rock in the excavation-damaged zone and plugged deposition tunnels is to verify that the requirements of the safety assessment are met. The chapter "Monitoring programmes for sealed areas" in State-of-the-Art report 2015 noted that the focus of a KBS-3 repository is on the bentonite buffer and the backfill in the deposition tunnels. In contrast to other barriers, the safety assessment requires that these two barriers must change *after closure* in order to fulfil their safety functions. The buffer and the backfill must become water-saturated in-situ in the sealed deposition tunnel in order for the repository to achieve its target state. A strategy for monitoring of a KBS-3 repository must therefore include a monitoring programme that shows that the evolution of the two barriers lies within the limits set by the safety assessment (Swedish National Council for Nuclear Waste, 2012a).

The value of a monitoring programme is realized by follow-up of the results. From the perspective of society, the value of monitoring in sealed areas lies in its contribution to the long-term safety of the repository. Follow-up requires a separate organization with specific criteria for intervention in the repository if the monitoring results deviate from their expected values according to the safety assessment. From the perspective of the project, such interventions can be very costly, but a monitoring programme can also contribute to cost reductions by development of simpler and more effective design premises.

According to the EU-project MoDeRn, the monitoring programme also creates added value outside the project, by improving relations between the project and outside stakeholders and by knowledge building in support of the design of future repositories. In the former case, the monitoring programme can contribute to transparency and greater confidence in the project actors, while in the latter case the value can be measured in economic terms.

Figure 7.1 Monitoring programme during different phases of a final repository (DPs = Design Premises)

Time / Area	Construction/ before operation	Operation during staged closure	Monitoring phase after operation but before final closure	After final closure
Repository's surroundings - above ground - boreholes	Technology and process exist - external environment - rock →	→	→	→
Repository's open (non-sealed) areas	Technology and process exist - characterization - design - work environment	Technology and process exist - characterization - design - safeguards - work environment - design premises - quality control	Technology and process exist - work environment - safeguards	
Sealed/plugged areas in or adjacent to the final repository	(Demonstration repository) ⇢	Technology and process need development - engineered barriers - excavation-damaged zone - more effective DPs	→	→

The value of monitoring must be balanced against the risk of disturbing the barriers and jeopardizing the repository's passive long-term safety. The chapter "Monitoring programmes for sealed areas" in State-of-the-Art report 2015 discussed the development of new measurement techniques to minimize this risk. The risk can also be handled by means of alternative designs of the repository. Instead of measurements in the entire repository, the measurement instruments can instead be installed in demonstration or pilot facilities. Such facilities should be located immediately adjacent to the final repository so that the measurement results will be representative of the final repository.[2]

In France, where legislation requires that it must be possible during a certain period to retrieve the deposited nuclear waste, monitoring via instruments installed throughout the repository is striven for. This permits continuous monitoring of conditions in different parts of the final repository, facilitating retrieval if necessary. Swiss legislation requires a monitored pilot facility which is representative of the final repository but spatially and hydrologically separated from it.

The goals, value and design of different monitoring strategies are discussed in the chapter, based on final repository projects in Europe. The design principles and the value of monitoring programmes for sealed areas are discussed in the first section. The extensive work with Posiva's demonstration facility and Switzerland's plans for a monitored pilot facility are then presented. Following this, the objectives of a recently initiated EU project with the participation of SKB and national organizations responsible for final disposal in nine other European countries and Japan are discussed.

The presentation has two important limitations: The focus is on monitoring of sealed areas and is assumed to be primarily concerned with the barriers in sealed (plugged) parts of the repository as staged (stepwise) deposition and closure proceeds up to final closure. The possibility of monitoring the state of the barriers in the repository during the initial post-closure period is mentioned, but is not the main focus.

[2] A demonstration or pilot facility directly adjacent to the final repository can be defined as "a repository in the same underground opening as the final repository and separated from it, but with all relevant features, events and processes (FEPs) representative of the final repository".

7.2 Processes and value chain

The EU project MoDeRn[3] (2009–2013) included national organizations responsible for planning and execution of final repositories in ten of the EU's Member States. The Council submitted an account of the technical development work in the state-of-the-art report from 2015. A consensus was also reached within the project regarding the workflow used in designing monitoring programmes ("MoDeRn Monitoring Workflow"), which is the basis for the work of developing monitoring strategies and decision-making in the current project Modern2020[4].

MoDeRn also discussed the value of a monitoring programme in sealed areas. MoDeRn's proposed workflow and a discussion of the value chain for a monitoring programme are presented in the following section. The intention is to provide a reference framework for the presentation of some national strategies and the description of expected work within Modern2020.

7.2.1 The process for designing monitoring programmes – "MoDeRn Monitoring Workflow"

The "MoDeRn Monitoring Workflow" is presented in one of the final reports from the project (MoDeRn, 2013).

The report emphasizes that monitoring and monitoring programmes shall be designed based on the needs of the final repository during construction and operation and to support the basis for decisions on staged closure up to final closure. It calls for a "top-down" approach aimed at a few overarching goals, which are then more narrowly defined in a hierarchy of sub-objectives. A reasonable interpretation is that this approach excludes monitoring programmes aimed at validating the safety assessment itself. Such validation must

[3] Monitoring Developments for Safe Repository Operation and Staged Closure (MoDeRn) was carried out 2009−2013 with 18 partners from 17 countries including the USA och Japan. The Swedish Nuclear Fuel and Waste Management Co (SKB) and the Department of Sociology at the University of Gothenburg participated from Sweden.

[4] Development and Demonstration of monitoring strategies and technologies for geological disposal (Modern2020) started on 1 June 2015 and will continue until 2020. The project is being funded within the EU's R&D programme Horizon 2020 and has 28 participants from 12 countries, including Japan. See: http://www.igdtp.eu/index.php/european-projects/modern2020 (downloaded 1 Dec. 2015).

precede monitoring and must be clearly distinguished from the objective of verifying that the barriers evolve within the limits set in the safety case.

MoDeRn establishes two overarching goals that all types of monitoring programmes should contribute towards:

– *Support decision-making.* Monitoring programmes shall continuously provide data as a basis for decisions on staged deposition and closure.
– *Support confidence-building.* Monitoring shall verify that the final repository is evolving within the limits set in the safety case and that its environmental impact complies with environmental requirements.

The two overarching goals can be broken down into four main objectives, each of which generates needs for monitoring programmes, which is reflected in Figure 7-1. The four main objectives concern (1) the internal environment with operational and occupational safety, (2) the external environment with environmental protection, (3) nuclear safeguards and (4) the repository's performance and ability to guarantee long-term safety. The first three objectives can be achieved by means of measurements on the surface and in the repository's openings. The fourth objective pertains to the evolution of the engineered barriers and the excavation-damaged zone in the host rock. The NEA's final report from the project *Reversibility and Retrievability (R&R) for the Deep Disposal of High-Level Radioactive Waste and Spent Fuel* (NEA, 2011) also emphasizes that monitoring should continue at least until final closure. The Council's State-of-the-Art report 2015 particularly emphasizes monitoring of the bentonite buffer and the backfill during the period up to water saturation.

The objective of monitoring the repository's evolution and ability to guarantee long-term safety can be further broken down into two sub-objectives: one to support continuous safety analysis of the repository and one to support pre-closure management of the repository. Monitoring should provide:

– data as a basis for continuous verification that the evolution of the repository complies with the requirements in the safety case for achieving long-term safety.
– data as a basis for decisions on staged deposition and closure of the final repository.

Monitoring requires an organization for planning, implementation and follow-up of monitoring results. MoDeRn foresees that the organization will manage three stages in the workflow:

– *Objectives, processes and parameters.* The above discussion of overarching goals and main objectives provides a starting point for this stage. The safety assessment and its methodology provide guidance for the continued work. Based on the safety functions of the different barriers, concrete processes are identified that affect these functions in order to determine which parameters should be measured to verify that the barriers meet the requirements in the safety case. For example, six safety functions are associated with the performance of the bentonite buffer in the KBS-3 concept. The most important process is water saturation, and an important parameter to monitor is the moisture content of the buffer. The workflow includes discussion with outside stakeholders regarding which parameters should be monitored. The results from stage 1 are a preliminary list of parameters that should be monitored, and this list is the starting point for the work in the next stage.
– *Monitoring programme design.* From an analytical viewpoint, this stage is the most laborious one. The feasibility of monitoring the different parameters in the preliminary list is evaluated. Relevant changes in a parameter may prove impossible to measure during the monitoring period because the time scale of the process is too long. An example is mineralogical changes in the bentonite buffer. In other cases, development of a new technique for measurement in sealed areas is required. Such technology development within the MoDeRn project was described in State-of-the-Art report 2015. Based on the list of measurable parameters, the monitoring programme is then designed. A very important step in this design process is determining trigger levels, i.e. limits within which measurement data must lie in order for the safety

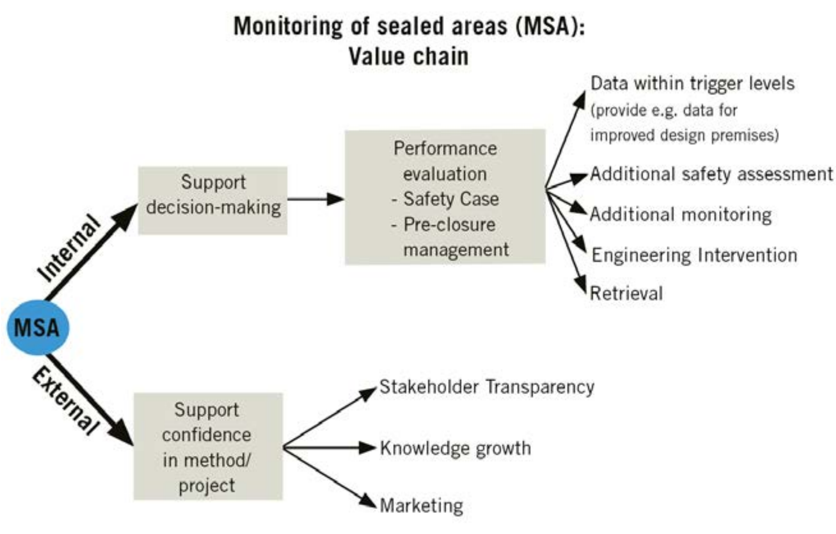
assessment's requirements on the corresponding safety function to be met. If the trigger levels are exceeded, appropriate responses are initiated.

– *Implementation and governance.* Measurement data are evaluated and assessed, and the results provide a basis for decisions within the project and for a dialogue with outside stakeholders.

7.2.2 The value chain

The goal analysis shows that value is created among three types of users of the results of the monitoring programme. Figure 7.2 schematically illustrates the value chain for a programme for monitoring in sealed areas in or immediately adjacent to a final repository. Society's needs and our perception of the needs of future generations provide the framework for the assessment of value.

Figure 7.2 Value chain for programme for monitoring in sealed areas in or immediately adjacent to a final repository



The first of two internal user categories is *experts and persons in charge of the long-term safety assessment,* which has been used to establish the safety case and determine trigger values. Comparisons with the results of the safety assessment provide the basis for decisions concerning staged (stepwise) deposition and closure. MoDeRn observes:

> An obvious pre-requisite for progress is that the information provided by monitoring does not shed doubt on the robustness of the safety case, but rather confirms the basis for long term safety and provides confidence to progress to the next stage/activity. Possible alternative options, however, must also be provided at each step – otherwise there would be nothing to decide.[5]

The expected outcome of the comparison is that the measurement data lie within the trigger values. But assuming that this does not lead to any decisions would be a hasty conclusion. Reassurance that the evolution of sealed areas is proceeding according to plan is important information to the second category of users, namely decision-makers in *project management* and, by extension, in *the regulatory authority.*[6]

An expected outcome can also lead to modifications. For example, SKB stipulates in its consultation response to the Land and Environment Court at Nacka District Court that "development of requirements, technology development and safety assessment must proceed iteratively" (SKB, p. 160, in Swedish).

An expected outcome that permits less conservative assumptions for the safety assessment could, for example, permit updated, more effective design premises. Such an outcome is also discussed in MoDeRn (2013, p. 55).

MoDeRn (2013) proposes a response scale with four steps for managing deviations from the safety case:

– Additional analysis of the assumptions and scenarios for long-term safety underlying the expected evolution and setting of trigger values.

– Additional monitoring and measurement to check/confirm the results.

[5] MoDeRn, 2013, p. 15.

[6] MoDeRn (2012) points out that "Monitoring for (Re)assurance" is an important value creator in interviews and discussions with members of the MoDeRn consortium. The conclusion is that for members of the consortium: "monitoring is about seeking confirmation that the facility performs as required and that the basic safety assumptions were correct." (MoDeRn, 2012, p. 8 and pp. 10–18).

– Engineering intervention.
– Retrieval of deposited nuclear fuel.

MoDeRn (2013) presents only a schematic approach to how these four steps are to be implemented. In the new project Modern2020, extensive efforts are planned to arrive at a consensus concerning responses (see section 7.4). In general, it can be observed that the two first steps do not require direct intervention in the operation of the repository. They should be able to be handled jointly by experts and persons in charge of monitoring systems and safety assessment. Steps three and four will have a great potential for affecting operation and will require decisions high up in both the project management and the regulatory apparatus.

Outside stakeholders are a third category of users for whom the monitoring system creates value. For the residents of a municipality with a final repository, continuous communication regarding measurements and outcome can improve transparency and increase public confidence in the project. For outside experts, the measurements contribute to increased knowledge and confidence, which are important in marketing the final repository concept.

Claiming that improved transparency, greater knowledge and marketing arguments create value is of course uncontroversial as long as the outcome of the monitoring is as expected. The situation becomes more complicated when it is necessary to climb up on the response ladder. In such a situation, unconditional openness is required on the part of the project in order not to compromise the value of the monitoring. It is important to underline that this value is ultimately determined by the needs of society and future generations, not by the needs of the operating organization.

7.3 Examples of strategies for monitoring

7.3.1 Different types of monitoring strategies

The second step in the MoDeRn Workflow addresses a general problem in connection with monitoring in sealed areas, namely management of the risk of disturbing the barriers' safety functions. One way to reduce this risk is development of non-intrusive monitoring techniques, including data transmission and energy supply of monitoring instruments. The chapter "Monitoring programmes for sealed areas" in State-of-the-Art report 2015 dealt with this response. Development of non-intrusive techniques can be combined with strategic considerations in designing the repository. For example, a monitored "mini-repository" can be incorporated in or built adjacent to the final repository. The following section gives examples of monitoring strategies aimed at balancing the risk of disturbing the barriers against the need to obtain measurement data that are representative of the final repository and can serve as a basis for decisions on staged deposition and closure.

An important distinction is between a "mini-repository" in a laboratory setting and a "mini-repository" incorporated in or directly adjacent to the final repository. A mini-repository in a laboratory setting is a part of the *R&D process* aimed at developing and validating the safety assessment. It can also be a part of the work of developing technology and methods for monitoring. A mini-repository in or directly adjacent to a final repository is part of the *industrial process* of building and operating a final repository with the goal of supporting the basis for decisions on staged deposition and closure. This is done by comparing monitoring results with the safety assessment's requirements and results. The industrial process thus assumes that the safety assessment has been validated.

Measurements in a laboratory setting can be done *in-situ* using sensors or *ex-situ* by measurements on extracted samples. The industrial process does not rule out *ex-situ* measurements, but such measurements in a mini-repository entail breaking up the repository and terminating the monitoring process.

The following distinctions are used in the chapter for different types of strategies for monitoring of sealed areas: Monitoring programmes can be executed in *experimental repositories* (such as Äspö), in *demonstration facilities* (such as in parts of ONKALO), in *pilot facilities* (such as Nagra's concept), in *test facilities* and in *the whole final repository* (such as is being developed by French ANDRA). The monitoring programmes may have different purposes and contents, but they are all designed to be as non-intrusive as possible so as not to disturb the barriers.

SKB's *experimental repository* on the island of Äspö has mainly functioned as a full-scale research facility for the whole KBS-3 method including groundwater flows, the barrier system and the backfill. In Äspö, the fundamental principles for KBS-3 have been developed and tested under repository-like conditions, i.e. in the rock about 500 m below the ground surface but without spent nuclear fuel in the copper canisters. The goal has thus been to test the KBS-3 concept at the system level, and the intention with the monitoring programme has been to contribute to validation of the safety assessment models. Seen from the perspective of the MoDeRn "Monitoring workflow", experimental repositories are a part of the R&D process and not examples of monitoring of the industrial process of building and operating a final repository.

Posiva's *demonstration facility* (parts of ONKALO) is located in the planned final repository near Olkiluoto and enables the KBS-3 method to be tested in its entirety with deposition of canisters (without spent nuclear fuel) and water saturation of buffer and backfill (Posiva, 2012). Furthermore, different systems for monitoring are being developed, including wireless sensors for presumptive use in the final repository. The work with the demonstration facility follows the MoDeRn Workflow and can be seen as an initial step towards monitoring of sealed areas in a final repository with the possibility of monitoring barrier performance in relation to the safety assessment requirements.

Nagra plans to build a *pilot facility* in Switzerland with radioactive waste directly adjacent to the final repository, but spatially and hydrologically separated. The waste, the backfill and the rock will be monitored for about 50 years after concluded deposition,[7] but before closure. Nagra characterizes the pilot facility together with the main repository as "monitored geological disposal".

Test facility is suggested as a common term for a monitored mini-repository incorporated in or directly adjacent to the final repository. The concept can embrace different repositories, from monitoring of one or several deposited canisters to monitoring of whole areas. Nagra's pilot facility can be regarded as a type of test facility. It is also possible that experience from Posiva's demonstration facility will be utilized to allow one or more of the first deposition tunnels

[7] Since ENSI prescribes progressive backfilling of the emplacement tunnels, this means that these tunnels are backfilled when emplacement/deposition is finished. This is also what is expected when the concept of staged deposition and closure is applied (ENSI, 2009, section 5.2.5).

with radioactive canisters to serve as a monitored test repository. Such test facilities can serve as references for the continuous decisions to be made during the staged closure of the repository.

ANDRA's concept in France is based on direct and indirect monitoring of the entire final repository. The monitoring equipment must be incorporated in the repository's design and the repository must be reversible for more than 100 years and permit waste retrieval.

It its preliminary verdict on SKB's application for a final repository, the Swedish Radiation Safety Authority (SSM) has pointed out the need for monitoring of hydrogeochemical parameters during the construction and operating phase. SSM believes that further demonstrations should be held in underground tunnels under conditions similar to those expected at the site of the final repository. The demonstrations should include both individual barriers and the integrated function of the entire barrier system before trial operation of the final repository can begin. SSM also points to the need for demonstration tunnels in the repository for verification of favourable rock and operating conditions. These requirements from SSM mean that different types of monitoring programmes must be developed, something that the Swedish National Council for Nuclear Waste has also recommended (Swedish National Council for Nuclear Waste, 2011, p. 92; 2012b, p. 42).

7.3.2 Posiva's strategy for development of a monitoring programme in the final repository

Premises

The premises and reasons for a monitoring programme that are described by Posiva (2012) in the following text section apply to the demonstration tunnels and the planned final repository for spent nuclear fuel (ONKALO) that is currently being built in Olkiluoto. Posiva took part in the four-year EU project MoDeRn, and experience from the international work in this project has guided the development of Posiva's monitoring programme. After a decision by the Finnish Government, Posiva has received a licence to build a final repository, but a new decision is required to put it into operation.[8] A programme for monitoring of deposited nuclear waste was initiated in a number of deposition tunnels in order to design and demonstrate the strategy for long-term monitoring of the engineered barriers (Engineered Barrier System) during deposition of spent nuclear fuel in ONKALO.

The focus is on the interaction with the safety assessment in accordance with the MoDeRn Workflow described in section 7.2.1. The Finnish final repository programme is one of seven national programmes that will be analyzed with respect to the need for monitoring in the ongoing EU project Modern2020 (see section 7.4). MoDeRn's analysis stages provide a list of parameters that should be monitored. This list serves as a point of departure for planning and design of the monitoring programme. The implementation of the monitoring programme will utilize the technology development being pursued in Modern2020. In particular, the use of wireless data transmission should be considered, along with how local (e.g. temperature, pH, water saturation) and more general (e.g. tomography) measurement results are to be combined. An overall requirement is that the monitoring programme must not compromise safety with respect to operation, environment and closure.

Thus, Posiva's monitoring programme has been designed with a focus on the technical and scientific measurements that are warranted by considerations of long-term safety and the environmental impact of the repository. Other aspects, such as the impact of the monitoring programme on public attitudes and confidence as well as social and political perspectives, are dealt with by other means. The "environment" is used here to include not just the biosphere, but also conditions in the host rock and the groundwater. Maintaining nuclear safeguards, ensuring operational and occupational safety, technical maintenance and ageing management in the repository will also require monitoring but lie beyond the scope of this programme.

[8] Finnish Government, 2015. Ministry of Employment and the Economy. Press release 12 Nov. 2015:
http://valtioneuvosto.fi/sv/artikeln/-/asset_publisher/posivalle-kaytetyn-ydinpolttoaineen-loppusijoituslaitoksen-rakentamislupa (downloaded 1 Dec. 2015).

Strategy

Preparing and implementing a monitoring programme requires the definition of clear investigation areas, chosen with reference to applicable legislation and in the light of experience from previous programmes, national and international, and using whatever modern and innovative measurement methods are available.

Posiva has defined six specific objectives, which relate to three of the four main objectives in the MoDeRn Workflow (section 7.2.1), but with an emphasis on the the repository's evolution and ability to guarantee long-term safety:

1. Long-term safety. Demonstrate that the conditions in the surroundings of the repository remain favourable for long-term safety, despite repository construction and operation.
2. Feedback to site characterization and modelling. Acquire data that can be used to define and test various models of the repository surroundings, which enhances the understanding of the site and its evolution.
3. Monitoring the environmental impact.
4. Provide feedback to the repository's construction and design regarding the impact of construction on the geosphere and the surface environment.
5. The engineered barriers. Monitoring the engineered barriers to confirm that they evolve as expected.
6. Compulsory radiological monitoring. Conduct the mandatory monitoring of radiation and of releases of radioactive substances in the repository's surrounding environment.

The relative importance of these areas varies over time, with the focus gradually shifting from site understanding towards safety and performance. Operation of the final repository is currently projected to start in 2023, after a few years of full-scale demonstrations and tests, and its duration is limited by the expected operating time of around 100 years. It has not yet been decided whether monitoring will continue after closure. It is not considered possible to foresee the technical premises and legislation that will apply at closure of the repository, and the decision whether or not to continue monitoring must be made then.

It is necessary to establish a number of clear objectives for the monitoring programme. Objectives 1 and 5 are closely related to the safety parameters for the rock and evolution towards a defined "target state" for the engineered barriers (Swedish National Council for Nuclear Waste, 2012a).

They also include most of the investigations that will require monitoring programmes in sealed areas. Another natural starting point for defining monitoring targets is to observe already-identified processes that affect the long-term safety of the repository. Then the monitoring results can provide feedback to site characterization and modelling, and to designers and builders, and be used to determine environmental impact and radiation levels. This is articulated in the remaining four objectives.

Reasons for the monitoring programme

Posiva describes how large openings in the rock are filled with air at atmospheric pressure when the repository is excavated, affecting the hydrology of the rock at depth (Posiva, 2012). This causes perturbation of the natural state of the geosphere, and repository operation (blasting, drilling, transport etc.) causes contamination with numerous substances that can affect the evolution of the repository. Influx of groundwater from the surrounding rock will continue for a long time, causing changes in flow paths, flow rates and salinity. Atmospheric oxygen (O_2) and carbon dioxide (CO_2) and possible contacts with surface water cause carbonatization and oxidation of the groundwater, and the decrease in pressure in the excavated spaces can lead to exsolution of dissolved gases such as methane. Degassing of the rock mass itself is also possible, which can lead to increasing concentrations of radon (posing a radiological hazard to the personnel), and result in water in fractures and pores in the rock being replaced with air. The environment changes from reducing to oxidizing. These and a number of other processes can be expected to occur both in ONKALO and in conjunction with the construction of a future final repository for spent nuclear fuel in Sweden (Swedish National Council for Nuclear Waste, 2012a).

Posiva says that site modelling is one of the main users of monitoring data and represents one of the main reasons why monitoring programmes are needed (Posiva, 2012).

New information can lead to changes in existing models, especially hydrogeological and geochemical models. Monitoring data can be used to test the validity of existing models of the repository and permit predictions of its future evolution. This includes e.g. how groundwater levels may change, along with flow direction and composition.

The engineered barriers with auxiliary components include copper canisters, bentonite buffer, tunnel backfill and concrete plugs and seals. These are key components in the KBS-3 method, and the reason for monitoring this system is to provide data to support predictions of their long-term evolution.

Expected processes in and around the repository

The copper canister is responsible for keeping the spent nuclear fuel totally isolated from the surrounding environment for as long as possible. *The bentonite buffer* is supposed to contribute to predictable mechanical, geochemical and hydrological conditions that are favourable for the canister by protecting it from external processes such as groundwater flows and movements in the rock. The buffer is also supposed to obstruct and restrict the transport of radionuclides if the canister should fail. *Backfill and plugs* in the deposition tunnels are supposed to help create a predictable and favourable environment for the canister and buffer. They are also supposed to obstruct and restrict releases of radionuclides and contribute to the mechanical stability of the rock surrounding the tunnels. *The closure* is supposed to protect and isolate the repository from intrusion by humans, plants and animals, and protect other barriers from flows of surface water such as meltwater and transport of harmful substances. *The properties of the rock* that render it suitable as a natural barrier to radionuclide transport are critical for the choice of a site for the final repository, and the rock is supposed to isolate the repository from climate change on the ground surface and prevent unwanted intrusion. The rock should also preserve favourable conditions for other barriers.

Posiva presents a number of processes that are related to the evolution of the engineered barriers and internal transport of substances. Some of the process are necessary for achieving the "target state" of the barriers, for example swelling of bentonite, while others will not occur if the other requirements on the barriers are met, for example transport of radionuclides. These processes with complications have previously been discussed in a series of reports from the Swedish National Council for Nuclear Waste (e.g. Swedish National Council for Nuclear Waste, 2012a; 2015).

The construction activity will lead to penetration of water from the ground surface down into the bedrock, and transport of rock rubble from underground blasting to the surface will lead to leaching of minerals from rock spoil, potentially releasing naturally occurring radionuclides or other pollutants into the biosphere. All processes that affect the ecosystems can be monitored by means of a monitoring programme.

Methods and limits

The objectives (1–6) presented above are characterized by a number of specific disciplines that provide a technical and scientific description of the monitoring programme. In this way they constitute an account of different monitoring methods and provide a better basis for setting limits and preparing action plans in response to the measurement results. Such disciplines include rock mechanics, hydrogeology, geochemistry, materials chemistry and materials physics (the engineered barriers, foreign materials) plus environmental science.

The measurement results within each discipline can be described in the form of "target values" and maximum limits, where the latter correspond to the trigger levels in the methodology on which the MoDeRn project is based and thus serve as a point of departure for an established action plan. There are a number of key processes that occur during both the operating phase and the post-closure period which affect long-term safety. These include water saturation and swelling of the bentonite in buffer and backfill. Unwanted mass losses can occur due to erosion and piping in compacted blocks and rings of bentonite or due to water penetration in fractures in the host rock. Posiva has determined target values for a number of anticipated processes, but so far limits are lacking for the engineered barriers that trigger the action plans described below.

A brief summary of methodology and experience from some of the aforementioned disciplines in the Finnish monitoring programme follows below (Posiva, 2012).

Rock mechanics

The monitoring programme for rock mechanics measures changes in the rock by means of continuous microseismic measurements, movements of rock blocks by GPS measurements and extensometer measurements in excavated spaces. It is particularly the area nearest the tunnel walls, the excavation-damaged zone (EDZ), that is considered to have the greatest impact on long-term safety, but this has been difficult to document. Attempts are now being made in ONKALO to characterize the area by means of a type of ground-penetrating radar.

Hydrogeology

Hydrogeological measurements have been made of groundwater pressure and flows in many deep and shallow boreholes, as well as in wells and ponds. The expected effect of the construction activities is a decrease in the hydraulic pressure at depth, which has been observed, while the shallow groundwater has not been notably affected. Changes in groundwater flow directions have been observed towards the open tunnels, especially where notable inflows occur.

Hydrogeochemistry

Chemical processes in the rock are extremely slow, and geochemical monitoring has focused on hydrogeochemistry. Changes (dilution) have been found in the deep groundwater in ONKALO, presumably due to the infiltration of surface water. Some measurements have revealed increased salinity, indicating infiltration of highly saline groundwater from deeper areas. Some concentration peaks of dissolved sulphide are found when different types of groundwater are mixed.

Materials chemistry and physics

Analysis and verification measurements of how the engineered barriers and the backfill have evolved are described here as materials chemistry, but also include other areas of chemistry, along with materials physics. The copper canister in the demonstration repository does not contain spent nuclear fuel, and the most important measurements consist of temperature, radial and axial strain and changes in position. Analysis of pH, redox level and characterization of the surface compounds (after dismantling of the canister) are also important. When it comes to bentonite buffer and backfill, water saturation and swelling are crucial parameters. They can be followed by monitoring of moisture content and pressure in different directions. The function of the concrete plug can be analyzed by flow measurement through and in the vicinity of the plug.

From monitoring to action

The monitoring programme is headed by a coordination group with a programme coordinator plus an additional coordinator for each discipline. The coordinators are responsible for planning and supervising the monitoring activities, checking and storing the obtained data, and reporting the results. The data is stored in Posiva's electronic database. The monitoring results for each discipline are published annually in a Working Report series, and the results from different disciplines are compared and combined where necessary to obtain a better understanding and integrated in an overall site model.

If the monitoring results indicate a deviation from expected values or expected evolution, this must be reported immediately to the persons responsible for e.g. design, construction, modelling and safety assessment. If the alarming results have been confirmed, decision on further action is made by the ONKALO Construction and Research Group (ORT) or, if the consequences in the form of costs and changes in the schedule of the project are very great, by the ONKALO Supervision Group (OVA). Further action depends on whether final disposal is still in the planning stage or spent fuel has already been emplaced. If unacceptable conditions have been observed in a limited volume of the host rock, deposition of canisters is interrupted there. If the observation concerns a large rock volume, the plans for final disposal can be changed or the requirements can be revised. Such a revision of the requirements must be justified by a safety assessment.

If waste canisters have already been emplaced in the concerned area, the consequences for the performance of the entire disposal concept must be determined. It must be determined whether more favourable conditions can be restored and how effective this can be done from the aspect of long-term safety. If the restoration of favourable conditions cannot be ensured, further action will be decided by comparing the risks of retrieval of waste canisters with those of leaving them in place.

7.3.3 Nagra: Monitored geological disposal in pilot facility

Framework conditions – design of final repository

Switzerland's Nagra[9] has a mission similar to that of Sweden's SKB, i.e. to plan and execute final disposal of radioactive waste with assured long-term safety. The organization is planning facilities for two types of waste: one for low-level and short-lived intermediate-level waste and one for spent nuclear fuel, high-level waste from reprocessing and long-lived intermediate-level waste. We will concentrate here on the second type of final repository, and especially on final disposal of spent nuclear fuel and high-level, vitrified waste from reprocessing of nuclear fuel, designated SF/HLW.

Based on 50 years' operation of the nuclear power plants, the quantity of waste will be:

- Around 1,600 canisters of spent fuel (SF) equivalent to 2,435 tonnes of uranium.
- 730 canisters of vitrified high-level waste from reprocessing (HLW).

[9] Nagra stands for Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (Swiss National Cooperative for the Disposal of Radioactive Waste).

The number of canisters corresponds to just over a third of the number expected to be deposited in the Swedish final repository for spent nuclear fuel.

The Swiss Nuclear Energy Act (KEG 2003) and the Nuclear Energy Ordinance (KEV 2004) set forth the general requirements on the final repository, including pilot facility, and monitoring. Regulations from the Federal Nuclear Safety Inspectorate, ENSI[10], specify the detailed requirements which the main facility and the pilot facility have to fulfil (ENSI, 2009). Nagra characterizes the final repository concept as "Monitored Geological Disposal", an expression which was also used by the expert group that prepared the Nuclear Energy Act (Hufschmied et al. 2002). According to Nagra's report to MoDeRn, the final repository should combine: "passive safety with a period of monitoring and the possibility of retrievability without excessive effort during the emplacement and observation period until final closure of the repository" (MoDeRn 2010, p. 56).

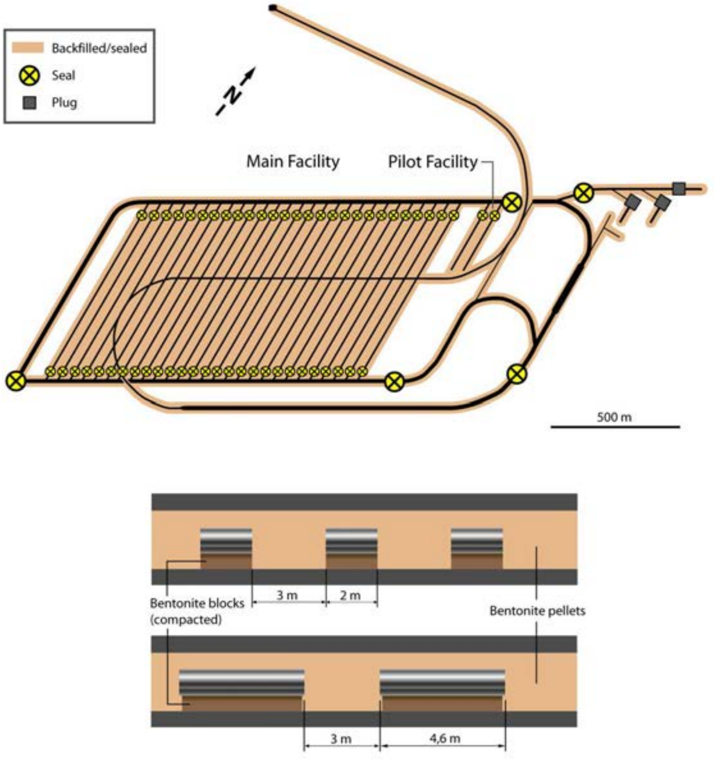
Figure 7.3 shows a schematic illustration of the repository, which is assumed to be located at a depth of 600 to 900 m in sedimentary rock (Opalinus Clay). The lower part of the illustration shows emplacement (deposition) in the emplacement tunnels of the canisters with vitrified waste from reprocessing and with spent nuclear fuel. The canisters rest horizontally on blocks of precompacted bentonite and the area between canisters and rock is backfilled with bentonite pellets. ENSI (2009) prescribes continuous emplacement and closure of the emplacement tunnels. The pilot facility is located next to the main facility, spatially separated but adjacent to it. As shown in the sketch, the pilot and main facilities lie behind the same seal when emplacement is finished. The emplacement tunnels including seal are about 800 m long, while the tunnels in the pilot facility are much shorter.

The use of bentonite for engineered barriers brings up similar questions regarding water saturation as in the KBS-3 case. The chapter "Monitoring programmes for sealed areas" in the state-of-the-art report from 2015 gives an account of the collaboration with the Swiss Federal Institute of Technology (ETH) in Zürich for develop-

[10] ENSI stands for Eidgenössisches Nuklearsicherheitsinspektorat (Swiss Federal Nuclear Safety Inspectorate).

ment of a seismic monitoring technique. With such a technique it would be possible to follow the water saturation of the bentonite without disturbing the barrier functions.

Figure 7.3 Schematic illustration of Nagra's planned final repository for spent nuclear fuel and vitrified waste from reprocessing



The lower figure shows emplacement of canisters with vitrified waste (upper tunnel) and spent nuclear fuel (lower tunnel) in the emplacement tunnels

Source: The figure is based on (MoDeRn, 2010, p. 60).

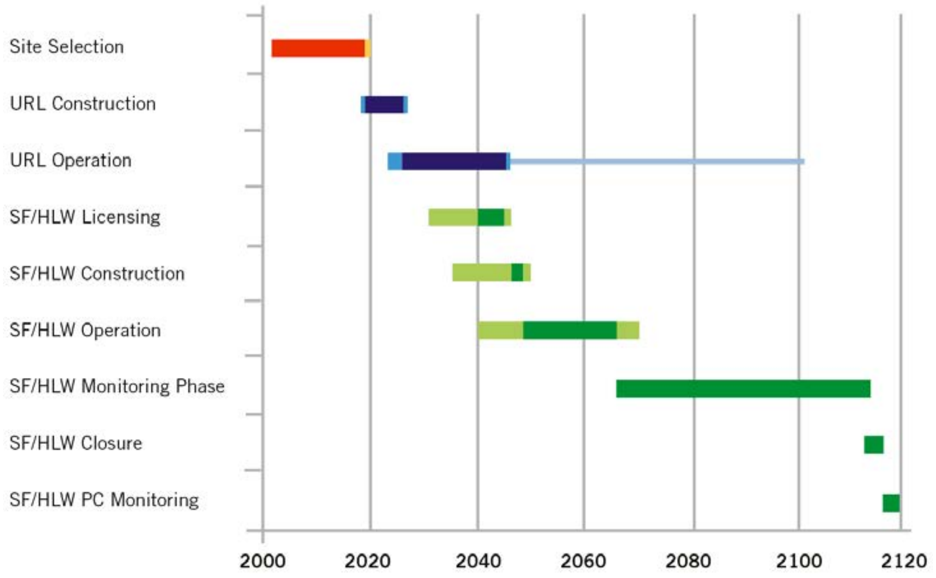
The pilot repository

The Swiss Nuclear Energy Act (KEG 2003) prescribes an extended "observation" or monitoring phase (Beobachtungsphase[11]) after concluded emplacement but before final closure. For this phase the owners of the repository must present a project for execution of monitoring and show how the emplaced waste can be retrieved "without great effort" ("ohne grossen Aufwand"). The Nuclear Energy Ordinance (KEV 2004, Art. 66) prescribes construction of a pilot facility to meet the law's requirements. The geological and hydrological conditions in the pilot facility shall be comparable ("vergleichbar") with those in the main facility, but the pilot facility shall be spatially and hydrologically separated from the main facility. The construction and emplacement methods shall be the same, and the pilot facility shall contain a representative, smaller quantity of waste. Monitoring shall provide evidence that the repository meets the requirements on long-term safety.[12]

Neither the lawmakers nor the Federal Nuclear Safety Inspectorate specify the length of the monitoring phase. Figure 7.4 shows that Nagra's own timetable for the final repository for SF/HLW proposes a 50-year monitoring phase beginning in 2065 and ending in 2115. According to the law, the Swiss Government shall determine the start and length of the monitoring phase.

[11] Definition of monitoring phase: "Beobachtungsphase: längerer Zeitraum, während dessen ein geologisches Tiefenlager vor dem Verschluss überwacht wird und die radioaktiven Abfälle ohne grossen Aufwand zurückgeholt werden können" (KEG 2003, art. 3).
[12] "Bei der Überwachung sind im Hinblick auf den Verschluss Daten zur Erhärtung des Sicherheitsnachweises zu ermitteln" (KEV 2003, art. 66).

Figure 7.4 Nagra's timetable for final disposal of spent nuclear fuel and vitrified waste from reprocessing (SF/HLW)



Lighter shades of colour mark the uncertainty in the indicated time spans.

URL: Underground Rock Laboratory. PC: Post-Closure

Source: Nagra (2009)

The requirements on monitoring in a pilot facility up to final closure to guarantee long-term safety thus have unconditional support in the Swiss legislation. The Federal Nuclear Safety Inspectorate's regulations define more detailed requirements on the pilot facility and the monitoring programme (ENSI, 2009, section 5.2.2).

Emplacement of canisters and backfilling must be finished in the pilot facility before emplacement may begin in the main facility. The ordinance's general requirements on similar geological and hydrological conditions, design and emplacement in the pilot and main facilities are now specified as requirements on the operation of the pilot facility. This operation shall be arranged so that:

a) The barrier system in the main facility is adequately reproduced.

b) The selection of waste packages is representative of the main facility's inventory.

ENSI (2009) clarifies the goal of the monitoring. The monitoring programme shall measure the evolution of the pilot facility and its geological surroundings so that it is possible to:

a) assess conditions and processes of importance for safety in the pilot facility and its geological surroundings

b) detect unexpected evolutions at an early stage

c) determine the effectiveness of the barriers

d) corroborate the evidence for the safety case.

ENSI (2009) also provides for the option of retrieving the waste in the pilot facility after the end of the monitoring phase and emplacing it in the main facility. This can be done if unforeseen events or planned interventions have damaged the barrier system and it cannot be repaired.

Nagra published its R&D programme for the final disposal process in 2009 (Nagra, 2009), and an update of the programme was planned to be published in the autumn of 2015. This update was not available when this chapter was written.

Some reflections on Nagra's strategy

The concept of monitored geological disposal realized by means of a pilot facility with monitored barriers is embodied in the Swiss nuclear waste legislation. Nagra (2009) discusses parameters to be monitored. According to Nagra's own timetable, construction of the repository will not begin until around 2040, so there is time for the extensive analyses that are required according to the latter part of the MoDeRn Workflow. Switzerland is one of the seven countries that, within the framework of Modern2020, will conduct an analysis of the national monitoring programmes. Modern2020 aims at developing a consensus ("collective opinion") regarding responses to the results of measurements conducted in the monitoring programme. Such a consensus should be a support in the continued workflow.

A monitoring strategy centred on a test facility or pilot facility raises several questions. The following three observations represent an initial attempt to identify some important issues:

- *Representativity.* A prerequisite in order for the pilot facility to provide reliable data is that relevant FEPs and links between them are the same in the pilot and main facilities. This requires extensive preparatory work, including measurements to verify this.
- *Validation of the safety assessment.* Nagra underscores in its report to the MoDeRn project (MoDeRn, 2010, pp. 61–62) that they interpret the ENSI regulations to mean that the main purpose of the monitoring programme is to evaluate the repository's long-term safety against the safety case, not to validate the safety assessment's models. This is quite in keeping with the discussion in section 7.2 above. In general it can be said that the monitoring programme makes extreme demands on previous validation of the safety assessment. If any doubt arises during the monitoring phase concerning the accuracy of the safety assessment, this can create a crisis for the entire final disposal process.
- *Competence.* ENSI's regulations permit transfer of canisters from the pilot facility to the main facility after the end of the monitoring phase. This enables the project management to manage the risk that the monitoring will disturb the barrier system, but also raises the question of available competence. A transfer of canisters would occur 50 years after emplacement of waste has been concluded in the main facility. This requires that both Nagra and ENSI, or their successors, have an organization that can guarantee that the necessary competence for emplacement is available at the end of the monitoring phase.

7.4 Planned continued development within the EU: Modern2020

Collaboration on monitoring systems between European national organizations with responsibility for final disposal is continuing in a new EU project, Modern2020.[13] The project is also described as a part of the activities within the EU's technology platform for geological disposal, IGD-TP (Implementing Geological Disposal of

[13] http://www.igdtp.eu/index.php/european-projects/modern2020 (downloaded 1 Dec. 2015).

Radioactive Waste Technology Platform).[14] The project's full name is "Development and Demonstration of monitoring strategies and technologies for geological disposal".

28 organizations from nine EU states and from Switzerland and Japan are included in the Modern2020 consortium. The project started on 1 June 2015 and will have a duration of four years. The project involves more than 600 work months distributed among six Work Packages (WPs).

The chapter "Monitoring programmes for sealed areas" in State-of-the-Art report 2015 described technology development for sensors and wireless data transmission. This technology development will continue in Modern2020, supplemented by development of alternative energy sources. Both new technology and monitoring strategies will be demonstrated on a full scale in the repository environment. The Work Package is called "Demonstration of monitoring implementation at repository like conditions" and tests will be conducted in Finland, Switzerland and France. "Full scale in-situ System Test, Finland" is being conducted in ONKALO by Posiva, VTT and SKB and is based on the work with the demonstration facility described in section 7.3.2. Nagra is conducting "The Full-Scale Emplacement (FE) Experiment" in an underground rock laboratory in Mont Terri.

The methodology for monitoring strategies and decision-making is being developed in a Work Package (WP2) under the leadership of SKB. The development work is divided into three tasks which correspond to the three stages in the MoDeRn Workflow described in section 7.2.1.[15]

Besides leading the whole Work Package, SKB will also lead the most laborious task, corresponding to stage 2 in the MoDeRn Workflow. SKB has greatly increased its involvement in Modern2020 compared with MoDeRn. The starting point for the work is analysis of seven different national programmes, and an important task for the Work Package is to develop a consensus regarding response planning: "to develop collective opinions on performance measures and response planning" (Modern2020 application part B, p. 29).

[14] http://www.igdtp.eu/index.php/presentation (downloaded 1 Dec. 2015).

[15] The three tasks are: "Decision-making Requirements, Monitoring Strategies and Approaches to Screening the Preliminary Parameter List", "Screening Test Cases", "Decision Making, Performance Measures and Response Planning".

Transparency and dialogue with citizens in the area around the final repository play a vital role in Modern2020. The aim is that this dialogue should start early on in the final disposal process, and the task is to study the role of the monitoring programme in the dialogue and for achieving transparency. Local stakeholders shall be given an opportunity to follow the work in both the strategic and technical work packages. The work package is being led by the University of Antwerp with the participation of e.g. the Department of Sociology at the University of Gothenburg, which is also in charge of one of the tasks.

The Swedish National Council for Nuclear Waste intends to follow the progress of the work within Modern2020.

7.5 Summarizing discussion

The topic "Strategies for monitoring programmes" has developed into an important area of cooperation for organizations involved in final disposal of spent nuclear fuel and high-level waste. From being the topic of a Thematic Network during the period 2001–2004 (European Commission, 2004), it went on to become the topic of the large projects MoDeRn (2009–2013) and Modern2020 (2015–2019). SKB has been the Swedish participant in these collaborations. The company is heavily involved in the ongoing Modern2020 project.

Two factors have driven the interest in monitoring: the need to support decision-making in a staged deposition and closure process, and the need to build confidence in the final disposal process among various stakeholders. From Sweden, the Department of Sociology at the University of Gothenburg is heavily involved in studies of this latter factor via its participation in the MoDeRn and Modern2020 projects.

Two other factors have driven the trend towards international cooperation to meet the needs of support for decision-making and confidence-building. Monitoring in sealed areas requires extensive technology development, which in turn requires financial resources and access to special facilities, such as an underground rock laboratory to simulate the environment in a repository. International co-operation is a natural response for managing costs and equipment. The second factor concerns managing the risk of conflict with the paradigm of passive long-term safety. The paradigm of passive safety is at the very core of geological disposal, and the national organizations that are responsible for the final disposal process have a common interest in arriving at a consensus on risk management.

There are *two perspectives* on risk management. The *first* is technical and strategic. The risk of disturbing the barriers can be reduced by the development and use of non-intrusive techniques. An appropriate choice of monitoring strategies is the second line of defence. Examples are Posiva's demonstration facility and Nagra's pilot facility. Posiva's strategy may shift towards a test facility, where one or more of the early deposition tunnels is equipped with monitoring equipment. The idea behind a demonstration, pilot or test facility is that the risk of disturbing the barrier function only arises in a mini-repository that is incorporated in or built directly adjacent to the final repository. The difficulty with these monitoring strategies is showing that the results from the mini-repository are representative of the final repository and constitute an effective and legitimate decision-making basis for continued staged deposition and closure. The question of representativity remains to be explored and resolved in e.g. Modern2020.

The *second* perspective on the relationship between monitoring and passive safety concerns confidence-building. On the one hand, confidence-building is one of the overarching goals of monitoring in sealed areas. On the other hand, an outside stakeholder could wonder how much confidence in passive safety exists within the project. Why monitor sealed areas if you are sure that the checks and analyses you perform before and during deposition guarantee the long-term safety of the repository? This question indicates the importance of clarifying that monitoring is a kind of reassurance that rock characterization and waste deposition have been done right. The purpose of the monitoring is not to validate the safety assessment. However, a serious crisis of confidence can occur if monitoring results deviate from what is expected and necessitate repairs or retrieval. The only way to avoid such a crisis of confidence is by a continuous and frank dialogue with outside stakeholders throughout the final disposal process. A clearly defined goal of Modern2020 is to find the forms for such a dialogue.

The discussion of strategies for monitoring programmes brings up questions which the Swedish National Council for Nuclear Waste has taken up in its reviews of SKB's RD&D programmes (Swedish National Council for Nuclear Waste, 2011; 2014) and in the Council's state-of-the-art reports concerning e.g. the organization of industrial projects and the relationship between the safety assessment and the construction and operating process and uncertainties in cost estimates (Swedish National Council for Nuclear Waste, 2010; 2012; 2013 and 2015).

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Committee terms of reference 1992:72

Scientific committee charged with the task of investigating questions concerning nuclear waste and the decommissioning and dismantling of nuclear facilities etc.

Decision at Government meeting of 27 May 1992.

Conducted by the head of the Ministry of the Environment and Natural Resources, Minister Johansson.

My proposal

I propose that a special scientific committee be appointed charged with the task of investigating questions concerning nuclear waste and the decommissioning and dismantling of nuclear facilities and of giving advice in these matters to the Government and certain public authorities.

Background

In Gov. Bill 1991/92:99 regarding certain appropriation matters for the budget year 1992/93 and changes in the national organization in the nuclear waste field, the Government proposed that the National Board for Spent Nuclear Fuel be abolished as a separate agency and that its activities be transferred to the Swedish Nuclear Power Inspectorate. The Bill proposed that the scientific council – KASAM – tied to the National Board for Spent Nuclear Fuel be given a more independent position and be tied directly to the Ministry of the Environment and Natural Resources as a commission instead of being administratively tied to an authority.

The Government (1991/92:NU22, rskr. 226) has decided in favour of the Government's proposal for a changed national organization in the nuclear waste field.

Thus, a special scientific committee charged with the task of investigating questions concerning nuclear waste and the decommissioning and dismantling of nuclear facilities and of giving advice in these matters to the Government and certain public authorities should be appointed.

Task

The committee should

– - every three years, starting in 1992, submit by not later than 1 June a special report describing its independent assessment of the state of the art in the nuclear waste field.
– - not later than nine months after the point in time specified in Section 25 of the Ordinance (1984:14) on Nuclear Activities, submit a report describing its independent assessment of the programme for the comprehensive research and development work and other measures which the holder of a license to own or operate a nuclear reactor shall prepare or have prepared according to Section 12 of the Act (1984:3) of the Act on Nuclear Activities.

The committee should also offer advice in matters relating to nuclear waste to the Swedish Nuclear Power Inspectorate and the Swedish Radiation Protection Authority when requested to do so.

Whenever necessary and economically feasible, the committee should undertake foreign travel to study facilities and activity in the nuclear waste field and arrange seminars on general topics in nuclear waste management.

The committee should comply with the Government's instructions to state committees and special investigators as regards the thrust of its proposals (Dir. 1984:5) and the EU aspects of the investigations (Dir. 1988:43).

The committee should consist of a chairman and at most ten other members. It should also be allowed to engage outsiders for special assignment whenever necessary and economically feasible.

Chairman, members, experts, consultants, secretary and other assistants should be appointed for a defined term.

The committee's task shall be regarded as completed when the Government has made a decision on the license application for a final repository for spent nuclear fuel and high-level nuclear waste in Sweden.

Petition

With reference to the above, I petition that the Government authorize the head of the Ministry of the Environment and Natural Resources

to appoint a special scientific committee – subject to the Committee Ordinance (1976:119) – with not more than eleven members charged with the task of investigating questions concerning nuclear waste and the decommissioning and dismantling of nuclear facilities and of giving advice in these matters to the Government and certain public authorities,

to appoint chairman, members, experts, consultants, secretary and other assistants.

I further petition that the Government order that the costs be charged to appropriations under the fourteenth title "Commissions etc.".

Decision

The Government concurs with the rapporteur's suggestions and approves his petition.

Committee terms of reference 2009:31

Supplementary terms of reference for the Swedish National Council for Nuclear Waste (M 1992:A)

Decision at Government meeting of 8 April 2009

Summary of task

The Swedish National Council for Nuclear Waste was established by a decision at a Government meeting on 27 May 1992 (dir. 1992:72). The Swedish National Council for Nuclear Waste shall investigate and shed light on matters relating to nuclear waste and decommissioning and dismantling of nuclear facilities etc. and give advice to the Government in these matters. Aside from the Government, important target groups for the Swedish National Council for Nuclear Waste are also concerned public authorities, the nuclear power industry, municipalities, interested organizations, politicians and the mass media.

The Swedish National Council for Nuclear Waste shall possess broad scientific qualifications in natural science, technology, the social sciences and the humanities.

The task of the Council shall be regarded as completed when the Government has decided on a final repository for spent nuclear fuel and high-level nuclear waste in Sweden.

These terms of reference replace the terms of reference from 27 May 1992.

Task

The Swedish National Council for Nuclear Waste shall assess the Swedish Nuclear Fuel and Waste Management Co's research, development and demonstration programmes (RD&D programmes), applications and other reports of relevance for the final disposal of nuclear waste. The Council shall – not later than nine months after the Swedish Nuclear Fuel and Waste Management Co has submitted its RD&D programme in compliance with Section 12 of the Act (1984:3) on Nuclear Activities – submit its independent assessment of the research and development activities and the other measures described in the programme. The Council shall also follow the work being done on decommissioning and dismantling of nuclear facilities.

In the month of February every year, starting in 2010, the Council shall submit a report on its independent assessment of the state of the art in the nuclear waste field.

The Council shall investigate and shed light on important issues in the nuclear waste field, for example by holding hearings and seminars, so that it can make well-founded recommendations to the Government.

The Council shall also keep track of other countries' programmes for management and disposal of nuclear waste and spent nuclear fuel. The Council should also follow and, where necessary, participate in the work of international organizations on the nuclear waste issue.

These terms of reference replace the terms of reference from 27 May 1992 (dir. 1992:72).

Organization

The Swedish National Council for Nuclear Waste shall consist of a chairman and not more than ten other members (one of whom also acts as deputy chairman). The members shall have broad scientific qualifications in fields related to the nuclear waste issue. It can engage outsiders for special assignments whenever necessary and economically feasible. Chairman, members, experts, consultants, secretary and other assistants shall be appointed for a defined term.

Timetable

The task of the Council shall be regarded as completed when the Government has decided on a final repository for spent nuclear fuel and high-level nuclear waste in Sweden.

(Ministry of the Environment)

The mission of the Swedish National Council for Nuclear Waste is to advise the Swedish Government in matters concerning nuclear waste and the decommissioning of nuclear facilities. The Council is a scientific committee whose members possess expertise in technology, science, ethics and the social sciences.

In February each year, the Swedish National Council for Nuclear Waste publishes a State-of-the-Art Report with the Council's independent assessment of the current state of the art in the nuclear waste field.

This year's report – SOU 2016:16, entitled *Nuclear Waste State-of-the-Art Report 2016. Risks, uncertainties and future challenges.*

The report examines a number of questions which the Council considers important to clarify in the Swedish final repository programme. These questions are dealt with in the following chapters:

- National competence management of importance for the final repository for spent nuclear fuel
- Obligations and responsibilities in connection with decommissioning and dismantling of nuclear power reactors
- Ethical perspectives on the agreement on support to the municipalities
- Earthquakes and earthquake risks in Sweden
- Risks and effects of low doses of radioactivity on man and environment
- Strategies for monitoring programmes in planned final repositories

The report can be downloaded at www.karnavfallsradet.se/en

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