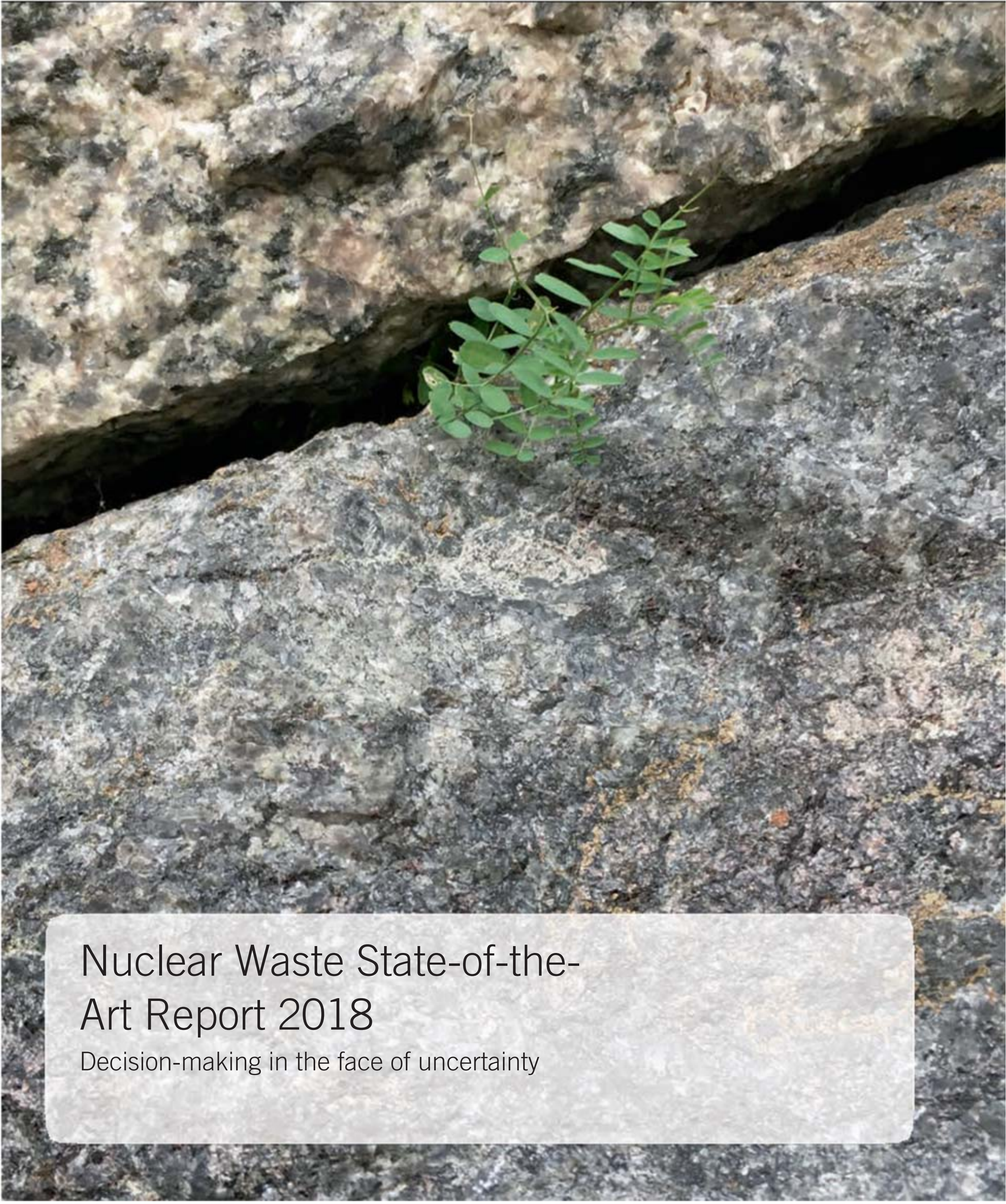

Nuclear Waste State-of-the-Art Report 2018

Decision-making in the face of uncertainty

KÄRNAVFALLSRÅDET
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Nuclear Waste State-of-the-Art Report 2018

Decision-making in the face of uncertainty

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The Swedish National Council for Nuclear Waste

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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 (the national advisor on nuclear waste issues) is an independent scientific committee whose mission is to advise the Government on matters relating to spent nuclear fuel, nuclear waste and decommissioning of nuclear facilities.[1] 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 that 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 eighteenth in the series) SOU 2018:8, entitled *Nuclear Waste State-of-the-Art Report 2018. Decision-making in the face of uncertainty*.

This report is endorsed by all members and experts of the Swedish National Council for Nuclear Waste. English versions of the Nuclear Waste State-of-the-Art Reports are also available for the years 1998, 2001, 2004, 2007, 2010, 2011, 2012, 2013, 2014, 2015, 2016 and 2017.

Stockholm, 20 February 2018

Carl Reinhold Bråkenhielm, Chairperson of the Swedish National Council for Nuclear Waste

Tuija Hilding-Rydevik, Deputy Chairperson of the Swedish National Council for Nuclear Waste

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[1] M 1992:A The Swedish National Council for Nuclear Waste. Dir. 2009:31.

Innehåll

Introduction

The Swedish National Council for Nuclear Waste (the Council) publishes a State-of-the-Art Report annually. This year's report is divided into two parts:

Part 1 deals with decision-making in the face of uncertainty. The Government must reach a decision on a final repository for spent nuclear fuel, and this decision will be made in the face of uncertainty. In itself, this is not an unusual situation for the Government, and decisions are made in different areas under such circumstance all the time, however, this project is unusual due to its level of complexity. (See the short overview below).

Based on its multidisciplinary approach, the Council provides some examples of different areas that feature uncertainties, and discusses the management of and approaches to uncertainties in decision making, both in general and when making a decision on a final repository for spent nuclear fuel in particular.

Part 2 includes a report on the Council's work and a short description of developments in the nuclear waste field in Sweden in 2017. A great deal has happened during the course of the year, for example in terms of the licensing process for spent nuclear fuel, the licensing process for the extension of a final repository for short-lived waste (SFR), and financing matters. A short description has been provided of the current state of affairs with the Government having taken over processing of the case of a final repository for spent nuclear fuel on 23 January 2018.

Background of the final repository, applications and the KBS-3 method

Concerning a decision on a final repository for spent nuclear fuel, there are many factors contributing to the complexity of the project. It is technically complex as the repository must be able to safely contain nuclear waste for at least 100,000 years – providing so-called long-term safety. The construction period for the final repository is unusually long, with the facility planned for completion in approximately 70–80 years. We do not know what developments will occur in terms of technology, the climate or society during such long time spans. Furthermore, there are no completed repositories for spent nuclear fuel that we can learn from.

A nuclear reactor is powered by nuclear fuel, and after approximately five years of usage, this fuel becomes so-called spent nuclear fuel. This high-level spent nuclear fuel is not regarded as nuclear waste under the Swedish Act on Nuclear Activities until it has been placed in a final repository. It is the responsibility of the reactor owners to take care of their nuclear waste and spent nuclear fuel. In order to take care of this responsibility, the reactor owners have jointly established the Swedish Nuclear Fuel and Waste Management Company (SKB), which plans, operates and constructs interim storage facilities and final repositories.

SKB is currently applying to construct and operate a final repository for spent nuclear fuel in accordance with the KBS-3 method. The applications concern a system comprising two facilities: an encapsulation plant in the municipality of Oskarshamn and a final repository in Forsmark, in the municipality of Östhammar.

The KBS-3 method is based on three safety barriers: copper canisters, bentonite clay and rock. The spent nuclear fuel is to be encapsulated in copper canisters, which will then be placed into a tunnel system 500 metres deep into the rock. The canisters will then be surrounded by bentonite clay, which will expand and protect the canisters. The plan entails depositing approximately 6,000 canisters, each containing approximately two tonnes of spent nuclear fuel, totalling approximately 12,000 tonnes. There are currently deposits totalling approximately 7,000 tonnes under water in pools in Oskarshamn (Clab).

SKB submitted its applications for licenses to construct, own and operate a final repository for spent nuclear fuel in March 2011. A license is required for this, and the licensing takes place in two separate processes. The Land and Environment Court at Nacka District Court processed the application in accordance with the Swedish Environmental Code (1998:808) and the Swedish Radiation Safety Authority (SSM) processed the applications in accordance with the Swedish Act on Nuclear Activities (1984:3). On 23 January 2018, the Land and Environment Court and SSM submitted their pronouncements, along with the applications, to the Government. The Government will then consider the applications, after which it will make a decision on whether the operations may be permitted under the Swedish Environmental Code (so-called admissibility) and on licensing under the Swedish Act on Nuclear Activities.

One challenge associated with assessing the applications is that they are based on reference designs that must become progressively more detailed, as it will take a considerable amount of time to construct and operate the repository. During the operating period, tunnels must be excavated and built at the same time as the canisters containing spent nuclear fuel are positioned, and surrounded by bentonite clay (deposited).

The pronouncements from the Land and Environment Court and SSM were submitted to the Government during the very final stages of work on this State-of-the-Art Report. Thus, the Council has not been able to use these as background documents during the writing process, and instead has only been able to reflect briefly upon them.

PART 1 Decision-making in the face of uncertainty.

The first part of this State-of-the-Art Report covers decision-making in the face of uncertainty, and the Council, assisted by its multidisciplinary approach, provides several different perspectives on the issue. This covers the Government's decision on a final repository for spent nuclear fuel and nuclear waste.[2] On 23 January the Land and Environment Court at Nacka District Court and SSM submitted the applications for licensing to the Government, along with their pronouncements, allowing the Government to progress with the licensing process. The introduction to this report (see above) includes a short background on the application and method.

Prior to the Government decision, the Council identifies some examples of different areas where there is a degree of uncertainty, as is unavoidable with a project of this magnitude. There are many areas to investigate, and those we describe may require continued investigation. The objective is not to issue firm practical advice, but rather to provide suggestions for ways to consider and approach the issue of decision-making in the face of uncertainty.

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[2] More information about fuel amounts and types can be found in SKB. 2011. "Toppdokumentet" ("The Top Document" in Swedish). In Ansökan om tillstånd enligt miljöbalken (1998:808) till anläggningar i ett sammanhängande system för slutförvaring av använt kärnbränsle och kärnavfall ("Application for licensing under the Swedish Environmental Code (1998:808) for facilities forming a cohesive system for the final disposal of spent nuclear fuel and nuclear waste" in Swedish).

1 Concepts and ethics surrounding decision-making in the face of uncertainty

As an introduction to part one, we have provided two over-arching sections concerning the issue of decision-making in the face of uncertainty. The first section deals with the concept of uncertainty. The objective of the section is to provide a greater understanding of the concepts of uncertainty and risk. Uncertainty can come in different forms, the issue of final storage is a complex one with many different elements, and a number of different strategies may be needed to deal with the uncertainties.

The second section looks at some of the key concepts within ethics. Using a concrete example as a starting point, different courses of action, the consequences of these courses, and questions of ethical relevance are analysed. Against this background, conflicts of duties that we may encounter in day-to-day life are considered, as well as those applicable to the selection of a final repository for spent nuclear fuel.

1.1 Uncertainty and risk – an introduction

The objective of this part is to identify the concept of uncertainty and look at how it is described in different contexts and what it may mean for risk assessment and risk management. First, the conventional views on the concepts of uncertainty and risk are described, and we look at how risks are evaluated and managed, and what challenges this entails. This is followed by a more thorough review of the concepts of uncertainty and risk. The chapter concludes with a discussion of how uncertainty and risk can be managed using different strategies. Particular attention is paid to the issue of nuclear waste.

An uncertain world[3]

The concept 'uncertainty' describes the situation that prevails when it is unclear whether something is true or false.[4] The word is used in a variety of ways in everyday language, and within a range of different scientific fields, including statistics, economics and physics. In terms of the environment and health, uncertain, potentially problematic situations are described using the associated concept of risk.

In conventional technical contexts, a risk is, in brief, a possibility of an adverse effect, i.e. the probability for being exposed to a hazard. For example, this could concern whether a chemical substance is dangerous in some way, and the degree of probability to which a person or other organism is exposed to the chemical. If it concerns carcinogens in toys used by children, the risks are greater even at low levels. If such substances are used in laboratories in controlled conditions, the risks are limited. Additionally, the risks are negligible for the many chemicals found in food that are not shown hazardous in tests, even at relatively high levels.

Key issues in the control of chemicals are the assessment of what levels are considered safe, and the levels humans are exposed to in different environments. This task concerns authorities and researchers in the fields of toxicology and epidemiology. When considering genetically modified plants, however, the emphasis is rather on explaining whether e.g. any parts of it can pose problems, whilst dispersal is generally assumed to occur sooner or later. For example, this could concern a field crop that has been engineered to include a gene that controls production of a substance poisonous for insect pests. This topic is the focus of work by molecular biologists and ecologists.[5]

A problem within both of these product-related areas is the prevailing uncertainty. Knowledge and data about hazard and exposure is often limited, which makes work on risk assessments more difficult. However, this need not preclude effective risk management.

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[3] A broad introduction to the issues covered in this section can be found in works such as Hansson. 2012. Riskfilosofi ("Risk Philosophy" in Swedish).
[4] However, this does not apply in issues of 'ethical uncertainty', see section 1.2.
[5] Karlsson. 2005. Managing complex environmental risks.

Uncertainty is also present in many technical systems, in particular those that are highly complex. Greatly simplified, risk assessments for a nuclear power plant involve describing the effects of different accidents, as well as the likelihood of each scenario occurring, individually for each scenario or for combinations of scenarios. The same applies to a geological final repository for highly-level nuclear waste from spent nuclear fuel.[6]

Risk studies may look at the consequences of a leakage of radioactive material and the likelihood of this occurring, for example in the event of any shortcomings in the different safety barriers in place. Here, there are uncertainties concerning characteristics as diverse as copper canisters (see section 3.1) and Swedish bedrock (see section 3.2). Furthermore, the long timespans involved make carrying out a risk analysis more difficult. It is extremely difficult to predict how technology and the environment will change over the course of millennia. The social systems that can impact upon safety regularly change even more, which creates even more uncertainties that can be pivotal in the assessment of risks. There is also an element of ethical uncertainty (see the next section, 1.2). Studying this issue requires knowledge of a range of scientific fields, from bedrock geology, materials science and toxicology, to history, law and ethics.

If the issue of uncertainty is broadened from products and technical systems to society in a wider sense, many sociologists argue that we are all living in an age of risk, i.e. risks characterise a large proportion of the debate, and in many cases are notoriously difficult to manage.[7] This perspective is interesting, but regardless of its validity, there are individual concrete risks that society must respond to in a constructive way. This is applicable to not least risks associated with final repositories and spent nuclear fuel.

[6] More information about the complexity is given in the second chapter of this report, as well as in works such as the Swedish National Council for Nuclear Waste. 2017. SOU 2017:62 Review of the Swedish Nuclear Fuel and Waste Management Co's (SKB's) RD&D Programme 2016.
[7] For example, see Beck. 1992. Risk Society; Giddens. 1999. Runaway World; Bauman. 2000. Liquid Modernity.

Conventional risk control[8]

The traditional method for controlling risks in society involves distinguishing between risk assessment and risk management. The former is considered a task for sciences and technology. A risk assessment is often based around four steps. The first step is to identify all conceivable noteworthy hazards in the form of potential negative effects, for example from radiation or environmental contaminants. This is followed by studies into the degree of exposure that could lead to such effects (often termed the dose-response relationship). The third step involves an investigation into the levels of exposure different groups of people, or other organisms, are exposed to in reality. The risk assessment is concluded with a fourth step, in which the risk in question is described, preferably quantitatively.

Risk management, on the other hand, is considered a normative issue that politicians regulate and that authorities and courts apply. This includes legislation on decision-making processes, with requirements for the assessment of risks or environmental impacts, as well as the regulations intended to prevent accidents and harm to the environment and health. For chemicals, the risk assessments are carried out to form the basis for restrictions on the most problematic substances, such as those that are carcinogens or may harm reproductive capacity. For spent nuclear fuel, the permit requirements for final repository facilities focus on requirements for environmental impact assessments, safety analyses and the highest permissible impact on the surroundings.

This traditional approach presumes a good degree of knowledge, relevant and reliable data, and a high degree of scientific logic amongst operators who are relatively unanimous. It is important that *researchers* and *politicians* adhere to their own domains, with the former expressing themselves in clear and comprehensible language, allowing the latter to act on the basis of the stated facts.

This situation rarely occurs when dealing with complex issues. Knowledge and data are often inadequate and it is not a rare occurrence that decision-making processes are disrupted by a lack of trust in experts and decision-makers, the work of advocacy groups,

[8] A broad overview of risk control can be found in Renn. 2008. Risk Governance. See also Karlsson. 2005.

and disagreements – more or less protracted – between different researchers and between politicians. This does not, in actual fact, need to be problematic if the parties clearly present facts and values.

Additionally, risk control measures are affected by communication about risks and how the risks are perceived by experts and the public. Laypersons do not always reach the same conclusions that emerge from an expert analysis, but it is well established that experts are also incapable to step out of their own shoes and away from their values.[9] There are also other parameters here that can affect the risk controls. One key example is whether the problems that may occur are reversible, and if they can be repaired or not.

In conclusion, it is clear that risks in most contexts have both objective and subjective dimensions, both of which must be considered in risk control measures. All of this is affected to a greater or lesser degree by uncertainties of different kinds.

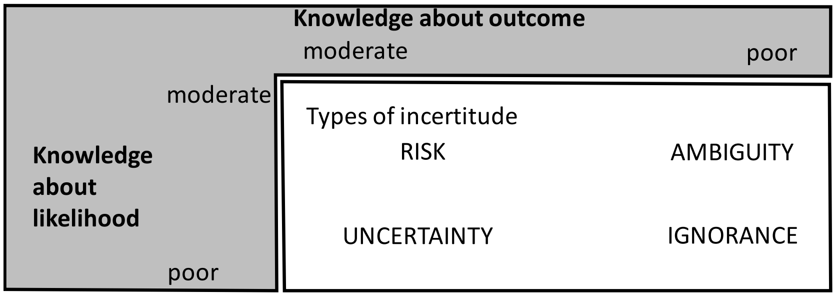
Types of uncertainty and risks concerning the environment and health

In terms of environmental and health effects, the relationship between uncertainty and risk can be further clarified. It is possible to differentiate four different 'incertitude situations: 'ignorance' (lack of knowledge concerning hazard and probability, when we know that we do not know), 'uncertainty' (knowledge on likelihood is lacking), 'ambiguity' (knowledge is lacking primarily concerning what effects could occur), and 'risk' (quantitative information is available about hazard and its likelihood, for example in the form of a risk assessment). These four situations can be illustrated in figure 1.1 below, presented by risk researcher Andrew Stirling.[10]

Beyond the diagram, there is another category that can be termed 'indeterminacy', for example, when a phenomenon is random by nature, or when the preconditions to determine a natural system's characteristics are not present (e.g. climate sensitivity – the level of global warming that will occur if carbon dioxide levels double).

[9] For a problematisation of the role of experts, see for example Jasanof. 1990. The fifth branch: science advisers as policy makers.
[10] As per Stirling. 2001. "Science and precaution in the appraisal of electricity supply options."

Figur 1.1 Types of 'incertitude. As per Stirling (2001)



The issue of a final repository for spent nuclear fuel can be divided into different sub-issues that can be placed in different squares in the figure above. Some concern 'risks' that are well known and quantified, for example regarding the health impacts of different doses of radiation (in addition to low dosage radiation, which still entails some uncertainty).[11] In other cases, researchers and operators not only disagree on the quantitative relationships, but also on the purely qualitative relationships. In the main hearing at the Land and Environment Court for the process concerning a final repository for spent nuclear fuel and nuclear waste during autumn 2017, one such situation became clear regarding copper corrosion, where both 'uncertainty' and 'ambiguity', as well as possibly even 'ignorance' characterised several of the discussions.[12]

Another way of describing risks is to supplement the magnitude of the effects and likelihoods with other parameters. The likelihood of a meltdown at a nuclear power plant is low, but the scale of harmful effects if one were to occur is vast. In other cases, the opposite may be true, for example when using fertiliser in agriculture, where the individual activity is well known and damaging effects are limited, but where the overall impact can cause major harm in the form of eutrophication. Other situations may revolve around risks with medium likelihoods and effects. This category includes a number of environmental contaminants, such as phthalates, which in several cases are characterised by reproductive

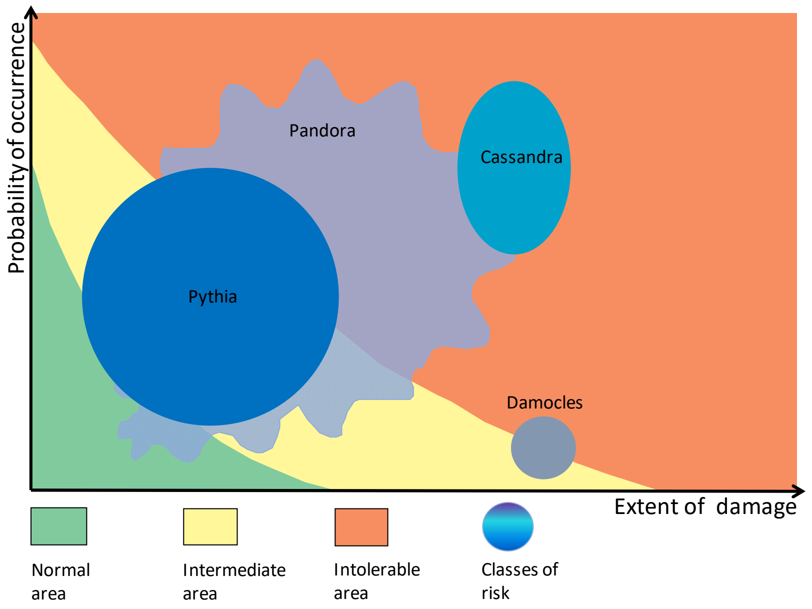
[11] The Swedish National Council for Nuclear Waste. 2016. SOU 2016:16 Nuclear Waste State-of-the-Art Report 2016. Risks, uncertainties and future challenges. See chapter 6.
[12] Land and Environment Court. Case 1333-11. Document appendix 608 record.

toxicity and can be found in everyday products. Some kinds of risks can also manifest as irreversible problems.

A striking illustration of these kinds of 'categories' of risks has been developed by German authorities and risk researchers, taking its category titles from Greek mythology (see figure 1.2 below).[13] The example above of a meltdown at a nuclear power plant would be termed 'Damocles', from the legend of the courtier at a feast who spent the duration of the meal sat under a sword suspended by a single thread. The likelihood of the thread snapping was low, but the consequences if it were to happen were deadly. Another Greek myth involves Pandora, who received a box created by Zeus and filled with evil. When Pandora opened the box, curses and evil spread around the world before she could close the lid. Invasive species that thrive and propagate in new environments and can cause irreversible risks are an example of this risk category. A final example is the prophetess Cassandra, who had the gift of being able to tell the future, however this was accompanied by the curse of never being considered trustworthy. An example of this is that researchers often highlight serious environmental risks at an early stage, yet are not taken seriously in society until far later. The role of carbon dioxide in global warming was highlighted as far back as the late 19th century, and after science-based warnings about the depletion of the ozone layer it took decades before effective measures were implemented.[14] The different risk categories are illustrated in the figure below, which also shows the degree to which risks can be managed.[15]

[13] Klinke and Renn. 2001.
[14] More information about these kinds of delays can be found in European Environment Agency. 2013. Late lessons from early warnings: science, precaution and innovation.
[15] Developed based on work by Klinke and Renn. 2001.

Figur 1.2 Different risk categories. Developed based on work by Klinke and Renn.



Where spent nuclear fuel should be placed in the figure above depends on the aspect in question. For some aspects the effects and likelihoods are well known, for example regarding certain radiation doses, with risks up to Damocles level, i.e. low likelihood of high exposure, but if such an incident does occur, the consequences will be serious for those exposed. Any leakages may be classified as Pandora, given the millennia-long periods these problems may last for. For many sub-issues, such as the integrity of the canister (incl. regarding different forms of corrosion, copper creep and different embrittlement mechanisms, such as radiation-induced embrittlement, hydrogen embrittlement and blue brittleness [see section 3.1 for further details]) uncertainty is the prevailing status, which is best classified as Pythia (referring to the mythical Oracle of Delphi, who often gave responses that were difficult to decipher). The risks here can be considered as encompassing different risk categories.[16]

[16] For more on this issue, see the Swedish National Council for Nuclear Waste. 2017.

These more complex ways of describing risks than the conventional risk model can make work on uncertainty management strategies easier.

Managing uncertainty and risks

Against a background of the uncertainty and risk classification scheme presented, it is possible to determine three kinds of strategies for risk management.[17]

First: if the magnitude of the effects is great and the likelihood low, or vice versa (minor effect but high likelihood), in general, preventive and science-based, technology-focused strategies are suitable. Often the degree of conflict here is low, and there is consensus on the risks and the view that they need to be managed. Experts play an important role in this context.

Secondly: if there is a high degree of scientific uncertainty about both the effects and the likelihoods, a precautionary approach is often required. For the last couple of decades the precautionary principle has also been prescribed by law, in both the Swedish Environmental Code and in EU treaties. We will take this opportunity to have a closer look at the principle.[18]

When discussing the precautionary principle, reference is often made to Principle 15 of the UN's Rio Declaration on Environment and Development of 1992, which states that:

> Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

Whilst uncertainty is not always sufficient as a counter argument, the principle does permit other counter arguments, and for this reason the wording here has been considered a source of weakness. A conflicting version can be found in the UN's World Charter for Nature, which rejects measures if full knowledge is not available, but as this is an impossibility, and a non-action is also a choice, there is a lack of logic in the wording here. Whilst the Precautionary Principle is subject to some debate in theory, in practice it is applied

[17] For example, see Renn. 2008 and Karlsson. 2005.
[18] For more on the origin of the Principle see Karlsson. 2006. See also Karlsson. 2005.

in many situations in many countries, and a systematic review of common objections shows that they are based on thin ice.[19]

In a study of how the Precautionary Principle is actually reflected in international agreements, the following version was presented: *If there is a threat, which is uncertain, then some kind of action is mandatory.*[20] This specifies that, once the principle is invoke, some management is needed, but not what. On this basis, the concepts of threat, uncertainty and action can be operationalised further, i.e. made tangible in clear decisions. This does not unambiguously require a ban, as is sometimes claimed, and in fact is more the exception rather than the rule. Often, the so-called 'reversed burden of proof', which is key for the application of the Principle, is referred to. This means that those, who wish to run operations that may cause harm, are responsible – as far as is practically possible, and not financially unreasonable – for proving that safety is at a satisfactorily high level and the risks are acceptable and motivated.[21]

For example, there is a major difference between whether the party introducing a chemical substance must first properly test it in order to rule out serious risks as far as is possible, or whether it is society that must show, supported by scientific consensus and unanimity between all EU countries, for example, that a substance that has already been introduced is problematic. Research clearly shows that chemicals policies suffer from the former situation prevailing, which is a key explanation for a range of different targets relating to achieving a non-toxic environment not being achieved.[22] Similarly, climate policy is characterised by the proof requirement that tightened targets or new emission reduction measures are not excessively expensive. When considered intuitively, it is a reasonable requirement, however, given the high degree of uncertainty, it can be difficult to provide evidence. However, the major problem occurs when those who recommend a 'business as usual' approach are not required to provide an equivalent degree of proof, e.g. that it would be more beneficial to society to not reduce emissions further. This

[19] The principle is discussed in works such as Sandin et al. 2002. A critical analysis can be found in Sunsteins. 2005.
[20] Sandin. 1999.
[21] Karlsson. 2006. shows how the principle can be put into practice. See also the general rules of consideration in the Swedish Environmental Code, in particular Chapter 2, Sections 1 and 3.
[22] For example, see Karlsson and Gilek. 2018.

asymmetrical burden of proof is one of the main reasons behind inertia in climate policy, and thus the difficulties in achieving democratically imposed objectives.[23]

Additionally, the Precautionary Principle – as an alternative to the standard utility-maximising decision-making criterion in environmental policy, which requires facts and knowledge – often brings into focus a risk-avoidance strategy of some form. One example is the maximin rule, which entails maximising the minimum benefit (or minimising losses in the worst case scenario).[24] A simple illustration of this could be that a farmer in Sweden has the opportunity to attempt to maximise their harvest, based on relatively predictable precipitation, chemical fertilisers and pesticides, and insurance systems if something goes wrong, whilst a farmer who lives in poverty in a country in eastern Africa, with precipitation that is harder to predict, and without the soil additives or the opportunity to take out insurance, will often avoid placing all their eggs in one basket, and will minimise their risk by cultivating a variety of crops, including both rain-dependent maize and perennial cassava, which is more tolerant of dry conditions. Strategies that are similar in principle are conceivable for everything from hazardous chemicals to nuclear waste.

Regarding a final repository for spent nuclear fuel in Sweden, the Precautionary Principle is implemented through the Swedish Environmental Code (see Chapter 2, Sections 1 and 3, for example), which as soon as the possibility of harm arises invokes a set of consideration rules, and places the burden of proof on the party undertaking an action or running operations. Licensing involves the implementation of requirements in the form of permit conditions regarding health and environmental safety (see section 2.5 on stepwise licensing). A key illustration is the issue of the copper canister and corrosion in an oxygen-free environment. The scientific uncertainties and controversies that exist between researchers raise questions such as which basic assumptions should be made in the face of uncertainty (corrosion or not) and which requirements for protective measures should be imposed (on the basis that such

[23] Alfredsson and Karlsson. 2016; Ackerman and Stanton. 2013; van den Bergh. 2017.
[24] See Hansson. 1997.

corrosion will or will not occur). The issue of division of the burden of proof is key for decision making.[25]

Thirdly: in situations with major effects and high probabilities, as well as minor effects and low probabilities, there is another strategy. Here, it is not unusual that risks are underestimated by decision-makers, despite prior warnings from experts, or are overestimated by the public, contrary to scientific conclusions.[26] In such cases, strategies characterised by a high degree of participation, sometimes called discursive strategies, can be useful. Cases such as the former can involve focusing on establishing scientific consensus and communicating this to political decision-makers. In the climate sector, the UN's climate panel, the IPCC, is one such forum. Cases such as the later can involve the application of methods to increase public participation in the decision-making processes (although not necessarily in final decision making). This is not always effective, but in essence it is in line with the international Aarhus Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters.[27]

On the topic of a final repository for spent nuclear fuel, these kinds of participation processes have been used extensively, from the overarching plan with municipal advisory referenda in certain municipalities, to consultation processes in the municipalities that have for some years been affected by and partaking in the permission and licensing process.[28]

The three strategies mentioned above are, naturally, a categorical selection. In practice, they often overlap and complement each other. When it comes to spent nuclear fuel, the three strategies exist in parallel, with certain variations over the years, from technically rational risk prevention and risk decreasing work, via precautionary assumptions about worst-case scenarios in parts of different safety analyses, to local participation processes, including local referenda.

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[25] See also Hansson. 2012; Hansson. 2010.
[26] Klinke and Renn. 2001; European Environment Agency. 2013.
[27] Löfstedt. 2005. Risk Management in Post-Trust Societies; Lidskog and Elander. 1999. "På väg mot ekologisk demokrati?". ("Towards ecological democracy?" in Swedish) More information about the Aarhus Convention is available at: http://www.naturvardsverket.se/Miljoarbete-i-samhallet/EU-och-internationellt/Internationellt-miljoarbete/miljokonventioner/Arhuskonventionen--om-ratt-till-miljoinformation-/ (accessed 30 January 2018).
[28] For example, see Johansson. 2008.

Currently, the fundamental issue is unresolved and a decision on whether the proposed final repository as per the KBS-3 method will be permitted by the Government, and the licenses that will apply if it is permitted, has not been reached. Three kinds of fundamentally different outcomes are conceivable – that a decision is reached and the issue is no longer in limbo; that the conclusion is a postponed decision due to deficiencies in the supporting information, requiring an alternative to be sought; or that a decision is made but potential alternatives are also sought in parallel.[29] Regardless of which outcome prevails in Sweden, it is likely that some degree of uncertainty will remain, in one form or another. This is where the three uncertainty management strategies presented may prove beneficial.

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[29] The three options can be termed 'closure', 'active postponement' and 'semi-closure'; for further information see Hansson. 2005. Decision Theory. A brief introduction.

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1.2 Ethical uncertainty

The aim of this section is, *first* to attempt to clarify what ethical uncertainty may entail by using a concrete example illustrating alternatives, consequences and what is morally relevant. *Secondly*, to analyse as special aspect of ethical uncertainty: the management of conflicts of duty in terms of a final repository for spent nuclear fuel.

An example of ethical uncertainty

Ethical uncertainty refers to a lack of certainty on what actions are morally right. We encounter this kind of uncertainty frequently, as private individuals, professionals, and political decision-makers. A tangible case can provide us with an example.

Jean-Paul Sartre – author, political activist, philosopher and Nobel Prize winner – wrote in one of his books about one of his students, who found himself in a situation of ethical uncertainty. It happened during the Second World War and France was under occupation. The student's older brother had been killed by the Nazis. The student now lived alone with his mother, who had recently been left by her Nazi-sympathising husband. The student now faced the following choice: either make his way to England and join the free French Forces, in doing so abandoning his mother, or stay with her and help her with her life.

One factor in the decision he faced was that the option of joining the free French Forces entailed major uncertainty. Would he be able to get there? Would he be playing a meaningful role? It might all lead to nothing, doing no one any good. On the other hand, helping his mother only benefited a single person.

> Which is most beneficial, the uncertainty of fighting as part of a group, or the more certain option of helping a particular person to stay alive?[30]

We will return to Sartre's advice later on. The important factor here is the ethical uncertainty – and how the student attempted to reduce the uncertainty. He wavered between two options; certain aspects of the situation encouraged him to go to England, whilst others pushed

[30] Sartre. Existentialismen är en humanism. 1966, p. 24. (Swedish version of "Existentialism and Humanism").

him to stay with his mother. It may be worthwhile to attempt to divide his dilemma up into three different questions:

1. What are the options?
2. What are the consequences?
3. What is morally relevant?

The options

To start with, we have the options. In situations of ethical uncertainty, this is an important, but often neglected issue. The philosopher Lars Bergström wrote his doctoral thesis on *The Alternatives and Consequences of Actions* (1966). In a newspaper interview about our freedom of choice, he put forward some choices and options he had been faced with. One example was when, after his dissertation, he had to respond to an offer of a teaching job in Australia. Then he came to his doctoral thesis:

> one of the ideas presented in the thesis was that options do not actually exist, and are instead things we invent to give structure to a situation. When facing a problematic situation, a person might only see two options, but if they think about the situation a little more, they could uncover a whole host of other options. / translated from Swedish/.

As an example, he takes the offer he turned down from Australia:

> I saw that as having two options, yes or no. However, I could always have said no and tried to find another post abroad that was more appealing. I didn't think about that when I only saw the two options ...
>
> Thinking about whether there are options other than those that first came to mind, and thinking through the consequences of these options are obvious pieces of advice that are often forgotten in a tense situation.[31] / translated from Swedish/.

Similarly, Sartre's student should have thought through his options. His alternatives appear evident: go to England or stay at home with his mother. But you can consider whether there are any other options. Could the student not stay at home with his mother, and

[31] Bergström. 2006. "Vi har ingen valfrihet" ("We have no freedom of choice" in Swedish). Svenska Dagbladet 11 September 2006.

work to help France regain its freedom from within the country (e.g. in the French resistance movement)?

On the surface, it appears that the student's situation does not have much in common with the decision on a final repository for spent nuclear fuel in Sweden. However, on a more general level, there are similarities. In the surrounding debate, the issue of the final repository has often been reduced to a yes or no to SKB's application for a final repository in Forsmark using the so-called KBS-3 method. But are there any other conceivable alternatives? Deep bore holes have been discussed, but in the background there is also a suggestion of a dry interim storage facility at ground level, pending new technical solutions. Naturally, another place could be chosen and/or modifications made to the KBS-3 method. The decision-making process leaves room for these kinds of consideration, in connection with the formulation of terms when the Government's decision is made. These terms could comprise requirements for a closer analysis of the options for different parts of SKB's proposal for a final repository solution. For example, one option could be a canister design other than that proposed, or another, more comprehensive investigation into an alternative site for the final repository. A general argument against these kinds of alternative part-solutions is that they can be both time-consuming and expensive. This leads us to the second question on ethical uncertainty, i.e. uncertainty regarding the consequences.

The consequences

Sartre's student was, above all else, focused on the issue of the consequences of the alternatives, i.e. the consequences of staying at home and supporting his mother, compared with the consequences of joining the free French forces in England. But in *what* respect should these consequences be compared? In the broadest sense, it is possible to compare the how good and desirable the options are. Would staying at home with his mother be more beneficial than travelling to England and fighting the Nazis with the free French forces? A problem with this comparison is, naturally, that the options are vastly different in nature – like comparing apples and pears.

Another difficulty is calculating the consequences. Sartre's student considers it particularly difficult to assess the England option, but if we speculate, it would have been possible to reduce the uncertainty through use of contacts and careful planning.

SKB has attempted to reduce the uncertainties regarding its options through a variety of scientific studies and technical developments. According to SKB (and SSM), the safety requirement is fulfilled, and the likelihood of a person in the proximity of the repository being harmed by radioactivity from the waste is less than one in a million. There are well-known arguments against this reasoning, primarily relating to the durability of the canister and its ability to contain the dangerous waste. This has given rise to a lack of scientific consensus, which, amongst other factors, became a defining feature of the proceedings at the Land and Environment Court in autumn 2017. How can a normal citizen of one of the municipalities concerned manage this lack of consensus – and how can the Government, which is tasked with making the final decision, overcome the issue?

The issue of how scientific disagreement on the consequences of technical environmental solutions should be managed has been discussed at length in socio-economic research.[32] One proposal for so-called 'Science Courts' was discussed as far back as the 1970s. The idea was for a scientifically-composed panel of scientific experts to hear the parties concerned in instances of scientific conflict, after which it would take a stance on the issue at hand. One criticism of the idea was that it does not pay adequate attention to the complicated relationship between facts and values.

A Swedish attempt at managing scientific conflicts that did take this complicated relationship seriously was the so-called Transparency Programme of the Swedish National Council for Nuclear Waste, implemented in 2007–2009. In the evaluation the programme was presented as follows:

> The Transparency Programme has been established and implemented based on the so-called RISCOM model, which can be described as a discussion method based on Jürgen Habermas theory of communicative action. The model or method aims to create clarity in fact- and value-based issues, and to ensure that all the important facts and arguments are presented, to allow

[32] The Swedish National Council for Nuclear Waste. 2014.SOU 2014:11 Nuclear Waste State-of-the-Art Report 2014.Research debate, alternatives and decision-making. In particular, see the chapter on scientific controversies, p.15–32.

> a well-founded decision to be made. The objective is not to come to a consensus. The model is a deliberative democracy based method for dialogue, which provides the preconditions and structure for scrutiny. The model is based on three so-called validity claims: "truth, rightness and sincerity".[33] / translated from Swedish/.

In the assessment of the programme, a lot of positives were highlighted, but there were also some criticisms of the implementation. The results of different surveys showed, amongst other findings, "that the seminars did not subject fact and values to sufficient scrutiny, that the moderators were not sharp enough and did not follow up on different arguments, and that the audience were not given the opportunity to be sufficiently involved." It is possible that some of these shortcomings stem from a lack of clarity in the formation of the programme itself, and were not just shortcomings in the implementation. Criticism directed at 'Science Courts' and the Council's Transparency Programme do not necessarily suggest that the basic idea itself is flawed.

What is morally relevant?

The third question focuses on the morally relevant aspects of the situation. Thus far, we have discussed options and consequences. However, the issue of ethical uncertainty may concern more than just options and consequences. Many feel that there are other elements that impact upon a moral assessment. In his discussion of the student's moral dilemma, Sartre explores Kant's perspective on ethics and his so-called categorical imperative, i.e. never treat other people only as means to an end, but rather also as an end themselves:

> Very well; if I remain with my mother, I shall be regarding her as the end and not as a means: but by the same token I am in danger of treating as means those who are fighting on my behalf; and the converse is also true, that if I go to the aid of the combatants I shall be treating them as the end at the risk of treating my mother as a means.[34]

[33] UCER. 2009. Utvärdering av Kärnavfallsrådets genomlysningsprogram ("Assessment of the Swedish National Council for Nuclear Waste's Transparency Programme" in Swedish), 2009, p. 9 http://www.karnavfallsradet.se/sites/default/files/documents/2009-utvard-genomlysnprg_umeauniv.pdf (accessed 30 January 2018).
[34] Sartre. 1966, p. 24.

According to many moral philosophers, besides the consequences of the actions, there are many factors that are morally relevant and that we are obliged to consider. This includes so-called duties, or actions that cannot be neglected, even if doing so would lead to better consequences. A well-known example is the duty to tell the truth. "Always tell the truth, children, that is what our parents told us" (from Tage Danielsson's monologue "Om sannolikhet" ["On probability" in Swedish], 1979).

Under this duty we are obliged to tell the truth, even if lying would bring about better consequences, indeed, even if the consequences would be better not just for one person but for all involved. When the then Swedish Prime Minister Olof Palme did not tell the truth in the late 1970s about the involvement of the then minister for justice in a brothel scandal, it was certainly done so under the conviction that the consequences would be better this way not just for Palme himself, the minister for justice and the whole government, but for society in general. Perhaps it could be said that, in the conflict between the principle of acting in a way that will ensure the best consequences and the duty to tell the truth, Palme chose to act in accordance with the consequence principle. (Whether or not this actually led to the best consequences is another issue – and the decisive issue in the view of most consequentialists).

Naturally, there can be uncertainty about our duties. For example, is it *always* morally wrong to lie or to break our promises? The uncertainty must be separated from the ethical uncertainty that arises when our duties conflict with each other. Which duties should we prioritise if we cannot adhere to all of them for some reason? One example is the duty to defend ourselves and our country against a violent aggressor, and the duty to not kill other human beings.

The conflict of duties in the management of spent nuclear fuel

The management of spent nuclear fuel entails some such conflicts. If actions are considered duties in accordance with the consequence principle, there may be a conflict between (1) the duty to defend the well-being of people who are alive now and (2) the duty to take into consideration the self-determination of future generations. In its nuclear waste programme, France has concluded that the well-being of future generations must be given equal weighting to that of people alive now, and that people who are alive now cannot be protected using means that restrict the freedom of action of future generations to recover the spent nuclear fuel. In its application, SKB has chosen a different path.

Another conflict may occur between (3) the duty to inform future generations and (4) to simultaneously prevent people in the future from causing harm through active intrusion into the repository. Some may argue for the placing of limits on information about the repository in order to prevent active intrusion in the future. However, many have stated the opposite, that:

> the best thing we can do is to generously equip future generations with what we have, as well as maintaining as much freedom of action as possible for future generations.[35]

A third example of a conflict of duties is (5) the duty to be economical with our resources and (6) the duty to make a final repository as safe as possible.

The duty to fulfil the latter may mean that we must renounce the duty to be economical and limit access to, for example, usable materials in the spent nuclear fuel. This is the implication of SKB's proposal (even though implementation of the proposal would not make it fully impossible for future generations to reclaim the nuclear waste).

How should these conflicts of duties be interpreted – and how should they be managed? These questions touch on another form of ethical uncertainty, and weighing up the different duties against each other. For example, the different duties could be ranked against each other, and naturally it has often been the case that safety has been given the main priority, pushing the duty to respect the self-determination of future generations into second place. One option is to seek out solutions that optimise observation of these duties, and that do not give one duty unrestricted precedence.[36]

[35] National Coordinator on Nuclear Waste. 1999. Ansvar, rättvisa, trovärdighet – etiska dilemman kring kärnavfall ("Responsibility, justice, authenticity – the ethical dilemmas surrounding nuclear waste" in Swedish), p. 23. More about information and knowledge preservation is given in section 2.3.

[36] A more in-depth discussion is available in Bråkenhielm. 2015. "Ethics and the management of spent nuclear fuel", spec. p. 400–403.

Concluding reflections

At the start of this article a return to Sartre's advice to his undecided student was promised. Surprisingly enough, he writes that he already knew what he would say to the student before he came. Sartre writes:

> …I had but one reply to make. You are free, therefore choose—that is to say, invent. No rule of general morality can show you what you ought to do: no signs are vouchsafed in this world.[37]

Sartre's view can be interpreted as meaning that ethical uncertainty cannot be overcome by any means other than taking a stand, i.e. an existential choice with no theoretical guarantees. This does not mean that a position should be adopted rashly. It could be preceded by a number of different considerations that then lead to the adoption of a position. Circumstances, options and assessments of likelihood are naturally relevant, alongside more general moral principles[38], however, ethical uncertainty cannot be overcome in the same way as a scientific hypothesis is shown to be true or false. On the other hand, a range of steps can be established and followed in a process that leads to a more secure adoption of a moral position than following Sartre's recommendation, and simply taking a stand and 'making it up', would do. Stepwise licensing is an example of one such process; this decision-making process is discussed elsewhere in this report (see section 2.5).

This does not stop Sartre being correct on another point, i.e. that there is always a jump between undertaking the most comprehensive and in-depth research possible and taking a stand. SKB's application features one such adoption of a position, but this involves an inevitable degree of discretion and cannot be described as a logical conclusion based on more or less well-founded premises. This also applies to those who criticised SKB's adoption of an ethical position and the argument for another solution. The judgement reached is a factor in the resolution of any ethical uncertainty, and perhaps why scientific differences of opinion are no surprise. In a key sense, there are no ethical specialists who can provide a definitive answer as to how to manage ethical uncertainties. When it comes to ethical uncertainty, citizens, politicians and researchers are in the same boat. We may be able to agree on the best decision-making method, but

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37 Sartre. 1966, p. 27.
38 Bråkenhielm. 2015, p. 401–402.

we will never have complete guarantees when it comes to our ultimate moral positions.

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2 Policy, law and decision-making in the face of uncertainty

In chapter 2, the multidisciplinary perspective is broadened to other fields of social sciences and law, as well as to politics.

The first section of the chapter provides the background to what environmental impact assessments (EIA) are, and the quality requirements that can be placed on the role of the EIA in decision-making.

If SKB is granted permission to build and operate a final repository for spent nuclear fuel, a decisive issue will be ensuring that skill levels in the relevant fields are maintained. Therefore, one section of the chapter covers competence management from a perspective of just over 70–80 years. For this reason we also discuss the preservation of information. How can we communicate with future generations about the final repository and the waste it contains, in order to avoid unintentional intrusions into the repository?

Two sections cover some key legal issues of relevance for a final repository for spent nuclear fuel. One overarching issue concerns responsibility, not least after the sealing of the final repository. The final section of the chapter covers the stepwise licensing as per the Swedish Act on Nuclear Activities. This is an important issue, as it may provide an opportunity to manage uncertainties.

2.1 Environmental impact assessment – on careful consideration

EIAs are a key part of the application process. An approved EIA constitutes a process condition for the application to undergo environmental court proceedings as per the Swedish Environmental Code, and a precondition for testing by the Government as per the Swedish Act on Nuclear Activities.[39]

SKB submitted its applications to construct, own and operate a final repository for spent nuclear fuel in the municipality of Östhammar in March 2011. The form and content of the application are regulated by the Swedish Environmental Code and the Swedish Act on Nuclear Activities. Licensing is controlled by these two laws, and the Swedish Radiation Protection Act (more details about legislation and the licensing process can be found under Swedish National Council for Nuclear Waste 2011). EIA must be in accordance with both the Swedish Environmental Code and the Swedish Act on Nuclear Activities. The requirements for the EIA document and EIA process are set out in chapter 6 of the Swedish Environmental Code.

The requirements for Environmental Impact Assessment (EIA) for the nuclear energy sector were introduced in 1992 in Sweden.[40] Since then, EIA has been a topic of discussion in relation to final repositories for spent nuclear fuel. What should an EIA document contain, has the consultation process been sufficient, how should the requirement for the management of alternatives be interpreted, how should the parallel requirements in different laws be managed, what risk issues should be considered, etc.

[39] The Swedish National Council for Nuclear Waste. 2011. Licensing in accordance with the Swedish Environmental Code and the Swedish Act on Nuclear Activities. Technical report 2011:2, p. 10.
[40] Concepts: The terms EIA document and EIA process are used here as general and overarching concepts for the sake of clarity. EIA is used as a collective concept for work relating to both the document and process. The EIA system refers to a country's legislation, supervision, implementation etc. The terminology here differs from the terminology used in chapter 6 of the Swedish Environmental Code before and after 1 January 2018. Concerning the new chapter six: http://www.naturvardsverket.se/Stod-i-miljoarbetet/Vagledningar/Miljobedomningar/Om-6-kap-miljobalken/ (accessed 30 January 2018).

This year's State-of-the-Art Report looks at the issue of decision-making in the face of uncertainty. In this section we describe the degree of uncertainty in work on EIA during the final repository process. We also focus on EIA's role in decision-making concerning a project with a lot of unanswered questions at the point of application, and that spans a very long period.

What kind of features should an EIA have for this kind of special operation? Firstly, we provide background on how EIA developed internationally.

It began in the USA in 1970

It is usually stated that the first, better developed and formalised requirements for EIA came about on 1 January 1970 with the USA's federal National Environmental Policy Act (NEPA).[41] The EIA legislation was introduced in the wake of major environmental conflicts, which are compellingly described in the 1962 book Silent Spring by Rachel Carson. The NEPA's requirements primarily concerned large-scale projects. Similar EIA systems were later introduced in countries such as Australia (1974), Thailand (1975), France (1976) and the Philippines (1978).[42] The EU introduced its EIA Directive in 1985. More than 100 of the approximately 190 countries in the world have now introduced some form of EIA system with a basis in legislation.[43] Organisations such as the World Bank also began work on EIA as bases for their grant decisions from an early stage.

Caldwell (1988) succinctly sets out the essence of the objective of EIA legislation in the USA, and should be read against the background of the harsh environmental consequences and conflicts that arose during the 1950s and 60s (stemming from pesticides, oil leaks etc.) The objective of EIA was: "to protect the public and the environment from the consequences of reckless or inadequately informed policies and decisions". Caldwell (1988) highlights that

[41] Hilding-Rydevik. 1986. Metoder för naturresursplanering med ekologisk grundsyn. En litteraturstudie över naturvärderingsmetoder m.m. Byggforskningsrådet ("Methods for natural resource planning with an ecological outlook. A literature review of nature valuation methods incl. the Swedish Council for Building Research" in Swedish), p. 33.
[42] Caldwell. 1988. "Environmental Impact Analysis (EIA): Origins, Evolution and Future Directions."
[43] Noble. 2010. Introduction to Environmental Impact Assessment. A Guide to Principles and Practice.

the objective was to increase the legitimacy of administrative decisions through public participation, to influence the behaviour of private industry, to change environmental priorities, and to change how administrative decision-making was carried out. Work with EIA required major new departures from the normal bureaucratic decision-making and planning process. Furthermore, a multi-sector and multi-disciplinary approach was required. EIA has been named as one of the most important innovations in environmental policy in the 20th century.

From the original description of environmental effects and consequences in a broad sense, and only for major development projects, EIA has, in legislation and in practice, been further developed to also cover plans, programmes, health, social issues, sustainability etc. The methods used to analyse, evaluate, assess, present and monitor environmental impacts have also been developed. A full profession of consults working on all kinds of EIA has developed in Sweden and internationally. As a field of research, EIA is vast on a global level, and EIA researchers and practitioners come together at a global level, for example, at the annual, major multi-disciplinary conferences organised by the IAIA (International Association for Impact Assessment, www.iaia.org), which was founded in 1980.

EIA became statutory for the nuclear energy sector in 1992

In Sweden, the idea of introducing EIA was discussed from the mid-1970s[44] and the Swedish Environmental Protection Agency drafted a basis for the system, using the EIA systems in place in Canada and the USA.[45] Despite different investigations, work and development of voluntary EIA requirements in a number of municipalities[46], the

[44] Hilding-Rydevik. 1990a. Miljökonsekvensbeskrivning i kommunal planering. Förutsättningar samt förslag till arbetsmetodik ("Environmental impact assessments in municipal planning. Preconditions and proposals for working methodology" in Swedish), p. 8.
[45] Nilsson. 1974. Ekologisk planering i Kanada och USA ("Ecological planning in Canada and the USA" in Swedish).
[46] Hilding-Rydevik. 1990b. Miljökonsekvensbeskrivning av projekt och planer i kommunal planering ("Environmental impact assessments of projects and plans in municipal planning" in Swedish), p. 12.

many discussions and proposals in the public sphere[47] and within research communities[48] about the introduction of an EIA system, its introduction was delayed. In 1988, when the environmental bill was reviewed in the Swedish Parliament, the Parliament decided against the Government's desire to introduce an EIA system in Sweden.[49] The EIA requirement was later introduced in 1991 in the then Natural Resources Act (NRL), (however, the Roads Act had featured such requirements since 1987).

From 1992, the EIA requirements in the NRL also applied to the Swedish Radiation Protection Act and the Swedish Act on Nuclear Activities. However, by 1992 the planning process for a final repository for spent nuclear fuel had already been underway since the middle of the 1970s.[50]

It might then be pertinent to ask how ideas were formulated about what EIA would contribute to decision-making in general, and to a final repository for spent nuclear fuel in particular?

Unclear legislation

Work on an EIA within the planning for a final repository for spent nuclear fuel began with a framework that was often unclear and under development. For example, the EIA requirements were obligatory in some cases, whilst in others the decision-maker would individually assess each case to decide whether an EIA process was necessary. This was the case for the Swedish Act on Nuclear Activities and the Swedish Radiation Protection Act.[51] A further source of ambiguity was that the wording of the law did not clarify what an EIA document should contain, or how the EIA process should be structured. Thus, the introduction of EIA requirements

[47] For example, Naturresurs- och miljökommittén (Natural resource and environment committee). 1983. SOU 1983:56 Naturresursers nyttjande och hävd ("Utilisation and traditions concerning natural resources" in Swedish).
[48] Westerlund. 1982. "Miljöeffektbeskrivningar. Del 3: Sammanfattning och kommentarer" ("Environmental impact assessment part 3: Summary and comments" in Swedish); Emmelin. 1983. "Planering med ekologisk grundsyn" ("Planning with an ecological outlook" in Swedish).
[49] Swedish National Audit Office. 1996 MKB i praktiken ("EIA in practice" in Swedish), p. 23.
[50] Elam and Sundqvist. 2009. "The Swedish KBS project: a last word in nuclear fuel safety prepares to conquer the world?"
[51] Petri. 1995. MKB som verktyg i beslutsprocessen i Sverige ("The EIA as a tool in the decision-making process in Sweden" in Swedish).

into the final repository process gave rise to a whole array of sources of uncertainty. This was analysed by a collaborative group established in 1993, amongst others, consisting of representatives of the supervisory bodies concerned with the testing of the final repository for spent nuclear fuel.[52] The ambiguities are also reflected in the talks and discussions at the international EIA seminar at the then KASAM (former name of the Swedish National Council for Nuclear Waste)[53] held in Luleå in 1994.[54] Questions discussed included what should the EIA document include, when should the EIA process start, and how would people know when it had started, what is the ultimate objective of the EIA process and document (basis for decision-making, democratic basis etc.), what experiences can be gained from other countries that are further along with the process? An additional part of the development of EIA work was the efforts made in the municipalities concerned. In 1997 the *EIA forum for studies into final repository systems in Oskarshamn* was established.[55] A similar forum was established in the municipality of Östhammar in 2003, the *Forsmark consultation and EIA group*.[56]

Despite unclear aspects in other respects, the EIA regulation clearly stated in 1992 that there must be a statement justifying the different location and design options, as well as a description of the consequences of the measures sought not being taken, i.e. the so-called baseline scenario.[57] Furthermore, it was stated in the NRL that the objective of EIA is to provide a basis for decision-making. The EIA document must contain a cohesive statement on the impact of the planned operations on the environment, health and conservation of natural resources prior to testing of the operations

[52] The Swedish Radiation Protection Institute. 1995. Miljökonsekvensbeskrivning inför slutförvaring av använt kärnbränsle m.m. ("Environmental impact assessment prior to the final disposal of spent nuclear fuel etc." in Swedish).

[53] The predecessor of the Swedish National Council for Nuclear Waste was the Coordinating Council For Nuclear Waste Questions, which was established in 1985 and known by the acronym KASAM. In 1992 the name was changed to the National Council for Nuclear Waste Questions, but KASAM was used in parallel with the Directive's name until 2007. In 2007, the name was changed to the Swedish National Council for Nuclear Waste.

[54] KASAM. 1995. SOU 1995:90 Kärnavfall och miljö ("Nuclear waste and the environment" in Swedish).

[55] KASAM. 2004. SOU 2004:67 Nuclear Waste State-of-the-Art Report. p. 116.

[56] KASAM. 2004, p. 114.

[57] Andersson et al. 1995. "MKB-förfarandet ur ett myndighetsperspektiv" ("The EIA procedure from an authority perspective" in Swedish).

being permitted or refused permission.[58] It was also clear that the final repository issue entailed operations that pose a threat to the environment, thus requiring an EIA process.

The NRL was a so-called umbrella law, meaning that it provided guidelines for EIA and its application in a range of other laws.[59] When the EIA requirement was introduced in the NRL, environmental legislation was spread across 15 different pieces of legislation. However it was later brought together under the Swedish Environmental Code, which came into force in January 1999, the EIA regulations of which applied/apply to the application and EIA submitted by SKB in 2011.

The wording of the Swedish Environmental Code (chapter 6)[60] which guided SKB's EIA and application, is clearer than it was in 1992 in terms of the objective and the EIA document and process. An EIA must always be included in an application, under both the Swedish Environmental Code and the Swedish Act on Nuclear Activities. The objective is to identify and describe the direct and indirect effects of the planned operations or measures on people, animals, plants, land, water, air, the climate, the landscape and the cultural environment; conservation of land, water and the physical environment in general; and other conservation relating to materials, raw goods and energy. A further objective is to facilitate a joint assessment of these effects on peoples' health and the environment.[61]

Despite clarification measures, the issue concerning the content of the EIA documents and process, the implementation and the quality remained a topic of discussion during the final repository process. For example, see the Swedish National Council for Nuclear Waste's State-of-the-Art Reports[62] and the Swedish National

[58] The Swedish Environmental Protection Agency. 1995. MKB i miljöskydds- och naturvårdslagen. Allmänna råd 95:3 ("EIA in the nature conservation act and the environmental protection act. General advice 95:3").
[59] Swedish National Audit Office. 1996, p. 24.
[60] As of 1 January 2018 new rules and concepts have been in place in chapter 6 of the Swedish Environmental Code. More information about the new chapter 6 is available for example from sources such as: http://www.naturvardsverket.se/Stod-i-miljoarbetet/Vagledningar/Miljobedomningar/Om-6-kap-miljobalken/ (accessed 30 January 2018).
[61] The Swedish National Council for Nuclear Waste. 2011.
[62] The Swedish National Council for Nuclear Waste.2011; The Swedish National Council for Nuclear Waste. 2007. Platsval för slutförvar av kärnavfall – på vilka grunder ("Site selection for a final repository for nuclear waste – on what grounds" in Swedish); KASAM. 2006.

Council for Nuclear Waste's and other operators' statements to the Land and Environment Court at Nacka District Court on SKB's application and EIA document.[63] The Swedish National Council for Nuclear Waste has, for example, stated that the EIA document should set out alternative locations for the final repository and options other than the KBS-3 method, as well as stating that the application as a whole must facilitate well-grounded decision-making.[64] Thus, a number of additions have been made to the application and the EIA document following criticisms and perspectives expressed by different actors.[65]

Quality in EIA work

So, what constitutes good quality in EIA, for documents and processes and for outcomes of the planning process? This is an important issue for the final repository process. This is also a major issue amongst actors in the EIA sector, and is still the subject of much discussion internationally, both in research and practical spheres.

In order to shed light on the international discussions underway, a couple of recently completed research studies have been outlined below. Bond et al. (2018) states that there are major differences in the theoretical bases for assessing the quality of EIA, as well as significant differences in how different kinds of actors assess the quality of EIA. The researchers reviewed the quality criteria within different sectors of society, after which they analysed their

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Kärnavfall - Vilka alternativ för metod och plats bör redovisas? ("Nuclear waste – what method and location options should be set out?")

[63] See SKB's response to the statement in SKB. Frågor och svar per remissinstans ("Questions and responses by body consulted" in Swedish). Appendix K:3.

[64] The Swedish National Council for Nuclear Waste. 2016. Yttrande över Svensk kärnbränslehantering AB:s (SKB) ansökan om tillstånd enligt miljöbalken i ett sammanhängande system för slutförvaring av använt kärnbränsle och kärnavfall ("Statement on the Swedish Nuclear Fuel and Waste Management Company's (SKB) application for licensing under the Swedish Environmental Code as part of a cohesive system for the final disposal of spent nuclear fuel and nuclear waste" in Swedish) (M 1333-11). Statement 31 May 2016. Stockholm.

[65] SKB. 2017. Summering av inlämnade dokument, rättelser och kompletterande information i ansökan om tillstånd enligt miljöbalken – hantering och slutförvaring av använt kärnbränsle ("Summary of submitted documents, alterations and supplementary information in the application for licensing under the Swedish Environmental Code – management and final isposal of spent nuclear fuel" in Swedish). Appendix K:10.

applicability in relation to EIA. They suggest the general criteria shown below for the assessment of the quality of EIA:[66]

Table 2.1 Proposed EIA quality dimensions, Bond et al. 2018

Efficiency	The extent to which the best outcomes possible are achieved through an IA process given existing constraints.
Optimacy	The extent to which the process follows best practice (e.g. international standards) rather than the minimum requirements in any jurisdiction.
Conformance	The extent to which an IA complies with set requirements.
Legitimacy	The extent to which individuals and society regard the process and outcomes of an IA as being reliable and acceptable.
Equity	The extent to which the impacts or benefits identified in an IA, and the steps taken to address the impacts or benefits, are evenly and fairly distributed across society.
Capacity maintenance	The extent to which the practitioners of IA maintain the skills and knowledge to achieve the other aspects of quality.
Transformative capacity	The extent to which the IA has empowered individuals or has changed values (institutional or individual) or increased knowledge and/or understanding.
Quality management	The extent to which the quality is measured, monitored and managed by those conducting the IA.

Effective EIA work

Does EIA work make a difference and is it effective? And what do we mean by effective? Effective in relation to what? A common way of assessing the effectiveness of EIA is through four dimensions[67,68]

- Procedural – policy and institutional infrastructure, level of adherence to the applicable regulations, actual practices.
- Substantive – degree to which EIA mitigates negative environmental impacts and affects the decision-making process.
- Transactive – degree to which EIA avoids delays and cost overruns, clarity of stakeholder roles and personnel with adequate skills readily available.

[66] Bond et al. 2018. “A contribution to the conceptualisation of quality in impact assessment.”
[67] Loomis and Dziedzic. 2018. “Evaluating EIA systems’ effectiveness: A state of the art.”
[68] The English term ‘Transactive’ is used in the English and Swedish versions of this report.

- Normative – level of wider goal or policy achievement, e.g. sustainable development and a democratic participatory process, minimising trade-offs.

Loomis and Dziedzic (2018) carried out an analysis of the dimensions EIA research has explored. The most common studies focus on the procedural dimensions, i.e. how EIA is carried out in different countries and for different kinds of issues (large and small projects, plans and programmes, and within different sectors, such as transport, physical planning, etc.) Less common are studies into substantive dimensions, i.e. how EIA contributes to the fulfilment of legal and political EIA objectives. Least common are studies into the transactive dimension, i.e. issues of costs and delays related to EIA. When it comes to the normative dimension, i.e. how EIA work contributes to the fulfilment of broader environmental-political objectives, such as environmental integration in decision-making or with sustainable development, studies do exist, however they are relatively few and far between.

EIA and uncertainty

Planning and decision-making involve making choices. Choices of how EIA work should be defined in time and space, as well as what is included in the 'project', what are the options to be assessed etc. These choices are based on facts and values, as well as negotiations and power play between those involved. EIA is no exception. This means that the EIA process and presentation of the consequences in the EIA document itself is marred by uncertainties of different kinds. Cardenas and Halman[69] have identified the following stages in EIA work where uncertainty can arise: when identifying options and impacts, when identifying criteria, when selecting options, when identifying management actions, when implementing management actions, and in managerial review and judgement. One way of reducing the uncertainties in the EIA procedure is to do as suggested in the latter part of the quote above.[70]

[69] Quote from Cardenas and Halman. 2016. based on Canter et al. 1988; Liu et al. 2008; Maier et al. 2008. in Cardenas and Halman. 2016. "Coping with uncertainty in environmental impact assessments: Open techniques."
[70] Cardenas and Halman. 2016.

The concepts uncertainty and risk are described in the initial part of this report (see section 1.1). In terms of the link between EIA and risk analysis, there are a number of efforts to integrate risk analysis into EIA.[71] EIA is then assumed to contribute to the identification of potential consequences, and the risk analysis to the analysis of the impact – probabilities, consequences, scope and frequency.[72] However, use of formal risk analyses does not tend to be specified as a routine part of EIA work.

Criticisms of EIA

Criticisms of EIA on the whole and internationally do exist, and are significant in places. Some of the criticisms are internal, concerning how and the topics on which research is carried out. However, some criticism also concerns the practical work – i.e. the appearance of EIA legislation, how EIA is implemented and the effect of the work on planning and decision-making. The criticism can largely be summarised as focusing on the fact EIA is primarily used based on a narrow legal requirement, rather than as an instrument to support decision-making that is positive from an environmental perspective.[73] In some cases, EIA does achieve its objective, however, its contribution to heightened environmental awareness and environmental protection is modest.[74] The EIA work is seen as being pro forma, i.e. something that must be done, but that has no greater value in the planning process as a whole.[75] Naturally, there are cases where EIA work does make a difference from an environmental perspective[76], however, it appears that the impact of the EIA depends largely on the degree to which decision-makers are open to ensuring the value of the environment from the very start,

[71] For an overview, see Zelenaková and Zvijáková. 2017. “Risk analysis within environmental impact assessment of proposed construction activity.”
[72] Zelenaková and Zvijáková. 2017.
[73] Runhaar et al. 2013. “Environmental assessment in The Netherlands: Effectively governing protection? A discourse analysis.”
[74] Runhaar et al. 2013. based on Cherp. 2001; Jay et al. 2007; Wood. 2003. in Runhaar et al. 2013. “Environmental assessment in The Netherlands: Effectively governing protection? A discourse analysis.”
[75] Hilding-Rydevik and Emmelin. 2013. Alternativ i miljökonsekvensbedömning och miljöbedömning. En pilotstudie. (“Options for environmental impact assessment and environmental assessment. A pilot study” in Swedish).
[76] Runhaar et al. 2013.

and the degree to which the options developed within the EIA coincide with the operators' interests.[77]

Consequently, the idea that EIA contributes to project sponsors and decision-makers contemplating and analysing action options and their environmental consequences in greater depth, and this then having the effect of directing planning and decision-making towards a more environmentally-friendly path, not come into full fruition in reality. However, Sheate (2012) shows that EIA has an important role to play: by clarifying the responsibilities of those involved, at a legislative level, and holding individuals, organisations and authorities responsible for their actions at an implementation level. Planning processes and the different stages of EIA are not restricted in their usage and can be implemented by all manner of actors for their own purposes.[78]

Contribution of the EIA to the planning process for a final repository for spent nuclear fuel

How can we then assess the EIA process implemented, the EIA document submitted by SKB, and the EIA's role in the decision-making that has taken place and will take place for some time to come? Once all the decisions have been taken in terms of licensing for operations, a full analysis can be carefully carried out. However, some conclusions can already be drawn.

The requirements for EIA to be carried out as a part of the application process for a final repository for spent nuclear fuel have led to a large amount of information about different environmental factors forming part of the discussions during the planning process, and part of the supporting material for the application, which would not have been the case otherwise. The issue of, for example, different options in addition to the KBS-3 concept, has also clearly been brought to the table. The requirement for consultations with different parties to be carried out has already been clarified and formalised.

[77] Runhaar et al. 2013.
[78] Enriquez-de-Salamanca. 2018. "Stakeholders' manipulation of Environmental Impact Assessment."

There are a few research studies into EIAs linked to the final repository process in Sweden. For example, one research study has looked at the issue of how different options have been managed in the final repository project.[79] The study reveals, on the basis of a thorough review of a large quantity of empirical and historical material, that with such a long process, it can be difficult to maintain clear formal and separate roles in EIA and planning work. In turn, this may have led to it being difficult to fulfil the requirements of EIA legislation regarding the presentation of alternatives to the KBS-3 method. Another study states that the extended consultation has provided non-governmental organisations with greater access and insight into the process than they would have had without the EIA requirements.[80] However, in Elam et al. (2010) the consultation is discussed in terms of an industrial strategy and a facade to favour the organiser's own objectives.

Conclusions

In this section we have highlighted the uncertainty surrounding EIA work in relation to the final repository project. The rules were unclear from the start, and later regulations also leave room for different interpretations. Furthermore, there is a great deal of criticism internationally of the EIA instrument as an environmental policy instrument. Despite this, we cannot escape the need to carefully consider the effects and consequences of a range of different activities and projects for the environment and humans.

The final repository project must be seen as a unique and challenging project (technically, in relation to potential environmental and health risks if the final repository does not adhere to the 100,000 year time horizon in terms of safety and costs) to plan, make decisions on and implement. Therefore, it can be considered reasonable to place very high requirements on the content and quality of the application, including the EIA document and process. There is cause to study the scope within which the EIA document and process fulfil these high requirements in greater

[79] Wärnbäck et al. 2013. "Shared practice and converging views in nuclear waste management: long- term relations between implementer and regulator in Sweden."
[80] Keskitalo et al. 2015. "Environmental Impact Assessment as a Social Process: The Case of Nuclear Waste Storage in Sweden."

detail. Thus far (January 2018), the Land and Environment Court has proposed that the EIA and the EIA process fulfils the requirements set out in the Swedish Environmental Code, and may, therefore, be approved.[81] This means that EIA has fulfilled one of the eight criteria for good quality listed in table 2.1, i.e. the criterion of fulfilling legislative requirements. However, questions remain as to how well the EIA for a final repository for spent nuclear fuel fulfils the other criteria and questions. It could be pertinent to question whether the EIA process and document have contributed to reducing uncertainty regarding key future environmental consequences? And what does an assessment of the EIA document and process for the final repository for spent nuclear fuel say about the quality of the Swedish EIA system in general? Has EIA had an impact on actors, the planning process and decisions in a direction that is beneficial for the environment and people?

[81] The Land and Environment Court at Nacka District Court 2018. Pronouncement 23 January 2018. Case No M 1333- 11. Document appendix 842, p. 11.

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2.2 Competence management

This text is a follow-up to the 2016 State-of-the-Art Report, in which the issue of competence management was examined.[82] The objective of the text is both to show that we have not yet exhausted all avenues of investigation here, and that the topic is in fact highly pertinent, and to highlight new developments since 2016's report.

Uncertainty regarding competence management within nuclear waste management

Even today, there are doubts regarding current and future competence levels and volumes within the sector monitored by SSM. Within the fields of radiation safety and nuclear safety, concern has grown over Sweden's ability to meet the needs of the future regarding competence management. This was highlighted back in 2012 by the International Atomic Energy Agency, IAEA, when it was established that Sweden was not completely fulfilling international requirements in terms of relevant training and education and national competence within the sector.[83] It is conceivable that planning, construction, operation and sealing of an envisaged final repository for spent nuclear fuel would increase the requirements for future competence management within radiation safety and nuclear safety even further. Furthermore, in the long term Sweden is facing the need to dispose spent nuclear fuel and nuclear waste being generated as a result of the decommissioning of nuclear power plants and the decontamination of the area the plants were located in. This, along with the nuclear power industry's decision to close down four nuclear reactors by 2020, has led to the Government tasking SSM with carrying out an investigation into long-term competence management within SSM's area of responsibility, with

[82] The Swedish National Council for Nuclear Waste. 2016. SOU 2016:16 Nuclear Waste State-of-the-Art Report 2016. Risks, uncertainties and future challenges.
[83] https://www.stralsakerhetsmyndigheten.se/contentassets/674e1c84c22f415495a41ae8bae1a2aa/201203-the-iaea-integrated-regulatory-review-service-mission-to-sweden-in-february-2012;
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the final report due by September 30, 2018, government decision M2016/03064/Ke dated December 22, 2016.[84]

The role of universities in competence management in Sweden

The Government has a number of direct means of control over higher education in Sweden, including appropriation directions and targeted initiatives. Indirectly, available research funds can also steer education and training, as researchers at universities are the ones responsible for providing the education and training. Overall responsibility lies with each individual university or institute of higher education to provide its students with high-quality education options relevant to different parts of society. This applies to bachelor's, master's and doctoral level education. The objective is to provide the students with an education that is of sufficient breadth and quality to facilitate employment within areas including but not limited to: decommissioning and decontamination of nuclear power plants; design, construction and operation of final repositories for short- and long-lived (radioactive) nuclear waste; encapsulation of spent nuclear fuel in special final repository canisters; transportation of radioactive material; and radiation safety.

As a nation, Sweden has a responsibility to maintain the necessary national competence within these areas, in order to fulfil the requirements of the EU's Radioactive Waste and Spent Fuel Management Directive until the final sealing of the repository is carried out.[85] One key factor explaining why many other European countries currently have a worse outlook than Sweden within the areas of competence SSM is monitoring (such as radiation safety and nuclear waste), is that SSM has carried out several investigations into national competence over the last 20 years, allowing it to identify and describe problems, and to take necessary measures.[86] The

[84] https://www.stralsakerhetsmyndigheten.se/contentassets/0e003d432c9e4572989c584b9a8d6f7e/regeringsuppdrag-om-langsiktig-kompetensforsorjning.pdf (accessed 30 January 2018).
[85] https://ec.europa.eu/energy/en/topics/nuclear-energy/radioactive-waste-and-spent-fuel; http://eur-lex.europa.eu/legal-content/SV-EN/TXT/?uri=CELEX:32011L0070&from=EN (accessed 30 January 2018).
[86] SSM. 2013. SSM2014-1013. Appendix 2 of the report drawn up following an appropriation direction, Nationell kompetens inom strålskyddsområdet ("National competence within the field of radiation safety" in Swedish), and references within the document.

investigation into long-term competence management currently underway at the Government's initiative may create the preconditions to satisfy future needs.[87] Regular monitoring of competence management is important as the landscape in this sector can change rapidly. As stated above, Sweden shares the problem of declining competence with a number of European countries, which makes the recruitment of European competence and workforce to Sweden competitive in these areas.

In a debate article in the November 21, 2017, edition of the Swedish newspaper Svenska Dagbladet, entitled "Kunskapsnation Sverige bromsas av högskolan" ("Sweden as a nation of knowledge is being held back by its institutes of higher education", in Swedish), the article's authors, Johan Eklund and Dan Brändström, write that "Higher education in Sweden is not set up to supply business and industry with the necessary competence. This poses a threat to our welfare and our ambition as a competitive nation of knowledge."[88] Many other similar perspectives have been expressed in the media and in other contexts. It could be stated that the Government and inspection authorities have a responsibility to ensure that the Swedish education system can provide competence at an adequate high level for sufficient numbers of people to facilitate fulfilment of long-term commitments. One such example is the safe disposal of radioactive waste from the nuclear power industry and other parts of society that have been granted permission by the Government to produce such material.

In order for a university to be able to provide education that is of sufficient breadth and quality at different levels, the funding for relevant research must be ensured, as the researchers at universities are also the ones providing the education. In terms of education and research within areas concerning radiation safety, nuclear technology and nuclear waste, it can be presumed that in certain cases this must be limited to a smaller number of universities and institutes of higher education, so that the necessary resources for education and research can be optimised without creating a monopoly. Thus, it would be desirable for the state funding

[87] https://www.stralsakerhetsmyndigheten.se/contentassets/0e003d432c9e4572989c584b9a8d6f7e/regeringsuppdrag-om-langsiktig-kompetensforsorjning.pdf (accessed 30 January 2018).

[88] https://www.svd.se/hogskolan-broms-for-sverige-som-kunskapsnation (accessed 30 January 2018).

framework for research and development to clarify which state research funders are responsible for providing a good level of research funding within areas of relevance for final disposal of spent nuclear fuel and nuclear waste. Furthermore, it is also pertinent to ensure that the level of funding available is adapted to suit existing needs. We take a positive view of the new open call released by the Swedish Research Council for research within the field of nuclear technology, with the outcome of the first application round released at the end of 2017. This is a step in the right direction and we look forward to seeing more such initiatives in the future.

Conclusion

We are currently experiencing a degree of uncertainty as time passes regarding the supply of sufficient numbers of people with advanced training to ensure the disposal of radioactive waste. Thus, we would like to highlight the importance of ensuring sufficient resources for education and research within the relevant fields, and the importance of the results of these efforts being followed up on over time in order to minimise uncertainty concerning long-term disposal of spent nuclear fuel, nuclear waste and other radioactive materials produced in Sweden.

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2.3 Preservation of information and knowledge in relation to final disposal of spent nuclear fuel and nuclear waste

Introduction

If we do construct a final repository for spent nuclear fuel, how can we best preserve the waste-related information and knowledge needed to protect future generations for at least 100,000 years, over the longer term? Preservation of information and knowledge is a multi-disciplinary issue that attracts international cooperation, one example of which is an expert group within the Nuclear Energy Agency (NEA), part of the Organisation for Economic Cooperation and Development (OECD), named 'Preservation of Records, Knowledge and Memory across Generations' (RK&M).[89]

As stated in the 2014 and 2015 State-of-the-Art Reports, the RK&M group has been meeting since 2011 to work on issues relating to the preservation of and access to knowledge about nuclear waste over multiple generations.[90] In particular, the group's work is intended to result in support for information management within the various national programmes for radioactive waste and spent nuclear fuel. From Sweden, the following representatives have been involved in the group since 2014: SKB, SSM, the Swedish National Archives, the Swedish National Council for Nuclear Waste, the municipality of Oskarshamn, and the municipality of Östhammar.

The aim of this section is to provide an overview on the progress of this work over the last three years. Problems relating to information and knowledge preservation are pertinent not least as the Government will shortly be required to issue a decision regarding permission, whilst simultaneously facing uncertainty as to how the management of information and knowledge preservation will be shaped regarding a future Swedish final repository. From this perspective, it is very much a decision that will be taken against a background of uncertainty in the form of ignorance. The ignorance

[89] The NEA is the OECD's special committee for issues of nuclear energy technology and related topics. See: https://www.oecd-nea.org/rwm/rkm/ (accessed 30 January 2018).
[90] The Swedish National Council for Nuclear Waste. 2014. SOU 2014:11 Nuclear Waste State-of-the-Art Report 2014. Research debate, alternatives and decision-making, p. 79; The Swedish National Council for Nuclear Waste. 2015. SOU 2015:11 Nuclear Waste State-of-the-Art Report 2015. Safeguards, record-keeping and financing for increased safety, p. 73–94.

here is as set out in the diagram presented previously in the section on the concepts of uncertainty and risk (see section 1.1), both regarding the information and knowledge about the final repository that will be needed to maintain its future integrity, as well as the likelihood of such information and knowledge getting lost or becoming incomprehensible to future generations. This also applies to the following stepwise licensing process. Added to that, the decisions to be made when the final repository is sealed will be entirely dependent on the information and knowledge available at that point. It is, therefore, of utmost importance that important information is not lost.

The work of the RK&M group

The group's work has progressed in two stages. The first, carried out between 2011 and 2014 involved a wide-ranging inventory effort, which provided an overview of how work on preserving information was progressing in different countries, an online reference work (a wiki) that is constantly evolving, and other elements. The achievements and still-pressing tasks were presented at a major conference in September 2014 and reflected on in 2015's State-of-the-Art Report.[91]

During the first stage, starting points were established for the second stage (2014–2018) as follows:

- Preservation of information, knowledge and memories after the construction of final repository facilities will help future generations to understand well-founded decisions about the facilities and their contents, as well as preventing accidental human intrusion.
- The creation of the preconditions for future generations to understand these well-founded decisions must form part of a responsible, ethically defensible and sustainable strategy for the management of radioactive waste and spent nuclear fuel.
- Measures for the preservation of information, knowledge and memories should be prepared at the same time as strategies for

[91] The Swedish National Council for Nuclear Waste. 2015.

the management of radioactive waste and spent nuclear fuel are established and realised.

- Systems for the preservation of information, knowledge and memories must be flexible and adaptable over time.
- A systematic way of working must be applied so that the different parts of the preservation system, known as strategic elements, complement each other, create preconditions for redundancy regarding the transfer of information, knowledge and memories and maximise their lifespan.

Of particular interest amongst these starting points is the third, which states that information preservation measures should be prepared at the same time as strategies for the management of radioactive waste are established and realised. The reason for this is, quite simply, that incomplete or incorrect handling of information during this stage may lead to a loss of information that is needed at a later stage, for example to make a well-grounded decision.

Since the end of 2014, work has been underway on the second stage, with a scheduled end date in spring 2018. Here, efforts have been partially narrowed and concentrated on a number of more of less concrete document types for the preservation of information about repositories for radioactive waste and spent nuclear fuel over very long timeframes. Below are examples of some different types, primarily ‘key information files’ and ‘sets of essential records’.

Key Information Files

Key information files are documents of approximately 50 pages or 100,000 characters, containing the most important information about final repository facilities, and hundreds or thousands of copies are distributed in paper form, in addition to digital versions. The information contained within them is of ‘high-level nature’, meaning that the degree of detail must be limited.

A proposed structure for the content of the files has been developed, suggesting that the files should include:

- The context of the key information file, along with its origin and objective, as well as basic facts about the radioactivity, radioactive waste, and spent nuclear fuel.
- The location of the final repository plant, the environment and the irradiation conditions.
- The design of the final repository plant, including the key built structures.
- An inventory of the key dangers, and how they are estimated to develop over time. This should also include non-radioactive poisonous substances.
- A review of the safety features, with comprehensive barriers to isolate radioactive waste and spent nuclear fuel, and the potential human and other impacts and their consequences.
- A summary and timetable for the updating of the key information file, as well as its distribution geographically and in the media.
- Instructions on where more detailed information can be found.

Alongside the overall structure, a proposal for a more detailed contents list has been developed. The timescale for the use of the files is intended to be several thousand years or longer.

Set of essential records

The second document type planned is the set of essential records. This is defined as a collection of the most important documents, selected alongside the creation of a final repository plant. These documents are needed to provide current and future generations with sufficient understanding of the repository system and its features, to allow them to be monitored and controlled, and to allow for any changes and for well-founded decisions to be made concerning them, including assessments of their consequences. In comparison with the key information file, with its limited volume and popular style of presentation, the set of essential records serves as a source of more detailed information about the repository system, and is primarily intended for specialists and researchers, as well as decision-makers and supervisory bodies. Despite this, access to the set of essential records must be as free as to the key information file.

The information contained within the set of essential records, like the key information file, is ‘high-level in nature’, but contains more of what is designated as measurement data about the facility, concerning its geographic location, geology, hydrology, meteorology, geochemical conditions, and seismology, as well as the design of the repository facility and information about maintenance and repairs etc. The set of essential records will also contain data about the radioactive waste and spent nuclear fuel stored in the repository. This data will also include descriptions and assessments of the environmental conditions, as well as the features of the final repository and general information about its history and legal legitimacy, such as documentation about the licensing processes. The timeframe for the use of the set of essential records is intended to be shorter than for the key information file, at a few hundred or a few thousand years. The reason for this is that the set of essential records contains far more information that is duplicated in fewer copies, as well as the higher requirements in terms of the specialist expertise required to understand the information.

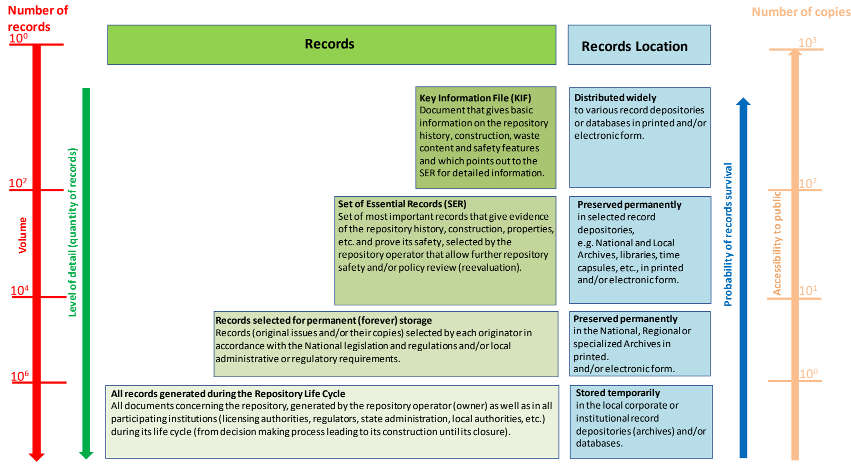
One issue that concerns both the set of essential records and the key information file is whether the content should be edited, revised and thinned out by future generations after both document types are competed. An advantage of more or less regular editing, revision and thinning out is that the comprehensibility of the information will be continually monitored and assessed. Another factor supporting continual updating of the information content is that new information may be added after the set of essential records is assembled. On the other hand, a disadvantage is the increased risk of the information becoming garbled. Another issue is the most appropriate media format for the set of essential records and key information file. In both cases, different formats can be used, probably more so in the case of the key information file than the set of essential records, due to the fact there will be less information in the former. One observation worth considering in this context is that it appears that the lifespan of the information medium is inversely proportional to its capacity, i.e. stone and clay tablets of earlier ages, with their relatively low information capacity, tend to have relatively long lifespans in comparison with modern digital media formats, the high capacity of which is counteracted by a relatively short lifespan.

Other document types

In addition to the information in the key information file and set of essential records, which are 'high-level in nature', RK&M has specified more document types containing information that is lower-level in nature, meaning that they contain a higher level of detail. This involves documents selected for eternal archiving, for the majority of which there are only one or a few copies. This may include the remnants of decisions and bases for reports. A further document type that overlaps partially with those above is the many documents created within the framework of establishing a final repository facility. The figure below shows the relationships between key information files and sets of essential records and these two more comprehensive document types.

Figur 2.1 Document types

The figure shows how the different document types (in green), such as key information files and sets of essential records, are considered to complement each other in an information preservation system. To the left is a scale indicating approximations of the volumes of the different document types, whilst the scale on the right shows an approximation of the intended number of copies of each document type.



Source: Processing of supporting documentation from RK&M.

Classes of strategic components

Together, these different document types form a class of strategic components, i.e. the class of collections of final repository documents, in which each document type forms a strategic element. Other classes of strategic components are memory institutions, where archives, libraries and museums are examples of comprehensive strategic elements. A further class is time capsules, another marker of final repository facilities in the landscape. Within the framework of RK&M's work, however, the other classes of strategic components have not been afforded the same attention and systematic analysis as that containing final repository documentation, despite an overview having been drawn up for each class of culture, education and art, as well as memory institutions.

In addition to the descriptions and overviews of the different strategic components and elements, RK&M will complete a catalogue of the different national and international legislation, rules and regulation of information management connected to the final disposal of nuclear waste. The countries covered are Canada, Germany, Hungary, Japan, Spain, Sweden and Switzerland, and the international organisations described are the EU, IAEA and OECD/NEA.

Memory of the World and new initiatives

Within RK&M, existing national initiatives for long-term preservation of information have been investigated. The most comprehensive and systematic of these so far is the Memory of the World programme, run by UNESCO since 1992. The programme was established in response to concern amongst some member states that there was a risk of many important documents being destroyed as their significance was not sufficiently recognised.

The programme identifies documents – an information medium that can be in paper, photo, film, data file, stone etc. format, or a collection of documents, in a library or archive for example – of significant value to humanity. The objective is to preserve memories of the world, make them more accessible, and increase awareness amongst decision-makers and the public of the importance of preserving documents. The Memory of the World programme is managed by experts, in the sense that the decisions as to which documents should be included in the record of world memories are made by an expert committee consisting of representatives from around the world. Today, there are almost 500 memories of the world recorded within the framework of the programme. The issue is, therefore, whether this institution or its working methods could be used to create better preconditions for the preservation of information about final repository facilities for radioactive waste and spent nuclear fuel.

As mentioned, RK&M work is set to conclude in spring 2018. At the same time, there are initiatives to continue the work on a more voluntary basis after the group's final report on its work is presented. One such initiative comes from the Swedish National Archives, which convened a working group at a meeting in late 2017 with the objective of planning a workshop to be held in the spring 2019 in Stockholm, on the theme of long-term information preservation, setting of goals, challenges and plans. Work on creating long-term sustainable information systems for final repository facilities for radioactive waste and spent nuclear fuel will, therefore, continue, even after work within RK&M has concluded.

The problems still to be resolved include:

– The definition of more classes of strategic components, not least adequate social institutions for the preservation of information and knowledge.
– The systematisation of the formulation and content of classes of strategic components and the standardisation of several strategic elements.
– Increasing public awareness of the problems associated with preserving information and knowledge over very long timeframes.

Final remarks

In conclusion, this section is important for decision-making in the face of uncertainties in the form of ignorance, both in terms of what information and knowledge should be preserved, and the likelihood of it being lost. In order to reduce this uncertainty, it is recommended that a number of strategies for information preservation measures are determined, and ideally these should be developed alongside the formation and implementation of radioactive waste management. The choice of information preservation strategies will, naturally, impact upon the sorting and propagation of the information produced some time ago, and that will continue to be produced during the completion of a final repository. Even at this stage, which Sweden has been at for some time, a lack of information can mean that the basis for future decisions is more deficient than it could have been.

For this reason, SKB should draw up a strategy for the management of information and knowledge preservation issues, including how long-term preservation of information and knowledge will be ensured. A reasonable short-term measure that could be implemented in the next research programme, the 2019 RD&D programme, would be to draw up a cohesive scientific analysis of the current state of knowledge and research needs in terms of the tasks of developing strategies for information and knowledge preservation for a final repository for spent nuclear fuel, as well as details of the practical consequences this kind of analyses would entail.

This proposal is in accordance with the Land and Environment Court at Nacka District Court's conclusion that a decision on a trial period investigation should be considered in areas such as information preservation.

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https://www.oecd-nea.org/rwm/rkm/ (accessed 30 January 2018).

2.4 Responsibility for final disposal of spent nuclear fuel

2.4.1 Before sealing the final repository

Responsibility for spent nuclear fuel being placed in a final repository

Reactor owners are responsible for ensuring that the nuclear fuel used in the operation of a nuclear power plant is permanently disposed of in a safe way. Or, as stated in the Swedish Act on Nuclear Activities, reactor owners must ensure "safe management and disposal of nuclear waste generated by the operation or nuclear material derived from the operation that is not reused."[92] The Swedish Act on Nuclear Activities also states that reactor owners must ensure "safe decommissioning and dismantling of facilities in which the operation shall be discontinued 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."

This means that reactor owners' responsibility for decommissioning may last many decades after the permanent discontinuation of the last nuclear reactor and the ceasing of electricity generation.[93] Thus, this is a long-term commitment for the reactor owner.

The reactor owners have jointly established the Swedish Nuclear Fuel and Waste Management Company (SKB) to take care of practical matters concerning management and final disposal of spent nuclear fuel.[94] SKB has established an interim storage facility for spent nuclear fuel, (Clab)[95], where since 1985 spent nuclear fuel has been placed in interim storage on behalf of the reactor owners, whilst awaiting the construction of a final repository. SKB is responsible for ensuring that the repository facilities the company establishes can store the spent nuclear fuel safely and without harm to the environment or human health.

This therefore entails some kind of shared responsibility, where the reactor owners, who are formally the owners of the spent nuclear

[92] Section 10(3 and 4) of the Swedish Act on Nuclear Activities (1984:3).
[93] The Radiation Safety Inquiry. 2011. SOU 2011:18 Strålsäkerhet – gällande rätt i ny form. ("Radiation safety – harmonising the law" in Swedish.), p. 494.
[94] The owners are Vattenfall AB (36%), Forsmarks Kraftgrupp AB (30%), OKG Aktiebolag (22%) and Sydkraft Nuclear Power AB (12%). See: http://www.skb.se/.
[95] Central storage facilities for spent nuclear fuel in the municipality of Oskarshamn.

fuel, must trust that SKB's private facilities fulfil the requirements the state places on final disposal facilities.

Responsibility for physical protection

The rector owners and SKB have joint responsibility under the Swedish Act on Nuclear Activities for nuclear safeguards for spent nuclear fuel. The Swedish Act on Nuclear Activities states that "nuclear activities shall be conducted in a way so that the requirements imposed for safety are met and the obligations are fulfilled as prescribed by Sweden's agreements aimed at preventing the proliferation of nuclear weapons and unauthorised dealings with nuclear material and such nuclear waste that comprises spent nuclear fuel."

The international nuclear energy organisation IAEA, along with the EU, which ensure that nuclear materials are not used for purposes other than those they are intended for, have, in different contexts, stated that there is no restriction in terms of time on this responsibility, even if the spent nuclear fuel has been placed in a final repository facility. See below for further information.

Responsibility for financing of the final repository

Under the Swedish Act on Nuclear Activities, reactor owners are also responsible for the costs of management and final storage of spent nuclear fuel and nuclear waste.[96] Under the Swedish Act on Financing of Management of Residual Products from Nuclear Activities, reactor owners are obliged to pay a fee (nuclear waste fee) to fund the future costs of final disposal of spent nuclear fuel, long-lived nuclear waste generated as a result of nuclear reactor operations, and the decommissioning and dismantling of nuclear reactors and other nuclear technology facilities.[97]

A state authority, the Nuclear Waste Fund, shall, for those liable to pay the fee, manage the nuclear waste fees paid through a fund. The Nuclear Waste Fund's annual report will make clear what

[96] Section 13 of the Swedish Act on Nuclear Activities (1984:3).
[97] Swedish Act on Financing of Management of Residual Products from Nuclear Activities (2006:647).

proportion of the Fund's finances correspond to each reactor owner. In addition to the funds held to cover a reactor owner's costs, each reactor owner must provide securities up to a certain amount.

Funds managed by the Nuclear Waste Fund shall cover both current and future costs of disposal. The basis for the financing of the disposal of nuclear waste is that the nuclear waste industry – not tax payers – must pay the costs.

Responsibility in the event of bankruptcy

One issue of interest is the situation that will arise if a reactor owner goes bankrupt for any reason. A bankruptcy estate is an autonomous legal personality arising following a bankruptcy decision. To manage an estate's assets, a bankruptcy administrator is appointed. The bankruptcy administrator is responsible for all of the estate's commitments, including any environmental debts and the ensuing responsibilities. In this case in accordance with both the Swedish Act on Nuclear Activities and the Swedish Environmental Code.

The key element of the bankruptcy administrator's task is to make full use of the creditors' common rights and take all measures to best promote a favourable and rapid liquidation of the estate. A bankruptcy estate may have limited cash assets and lack the means to pay for continued management of the spent nuclear fuel and ongoing environmental measures until a final repository is permanently sealed. One issue that may arise is whether the funds held by the Nuclear Waste Fund may also be utilised by the bankruptcy estate to pay for ongoing environmental measures. Additionally, the bankruptcy administrator may have an interest in selling the estate's property, e.g. by retrieving the spent fuel and selling it to another party that is interested in it. Naturally, a condition for this is that retrievability is technically possible, and that permission can be granted under the Swedish Act on Nuclear Activities.

2.4.2 After sealing of final repository

Where does responsibility lie after a final repository has been permanently sealed?

To establish where responsibility lies after the sealing of a final repository, the regulations in both the Swedish Environmental Code and the Swedish Act on Nuclear Activities must be taken into consideration. We then work on the basis of what is prescribed in currently valid legislation. The legislative situation in the year 2100 is not something we can speculate on.

Reactor owners are, under the Swedish Act on Nuclear Activities, still the owners of the spent nuclear fuel stored permanently in the final repository facility. After the final repository is permanently sealed, the reactor owner's responsibility is primarily an issue of so-called physical protection, i.e. ensuring unauthorised persons cannot access the spent nuclear fuel. The responsibility lies ultimately with the owner of the spent nuclear fuel, i.e. the reactor owners.

However, SKB, as the facility owner of the final repository, is running nuclear technology operations as specified under the Swedish Act on Nuclear Activities, and is therefore also responsible for organising the physical protection of the spent nuclear fuel permanently disposed of in the facility. Thus, this is a case of shared responsibility.

Responsibility for the physical protection of the plant applies for as long as there could be potential interest in accessing the fuel for military or civilian purposes. There are no further limits on this responsibility.

The operator, in this case SKB, in addition to responsibility for taking measures to ensure physical protection of the facility, is also responsible under the Swedish Environmental Code for remedying damage and harm to the environment[98] that has occurred as a result of operations at the final repository.[99] The after-treatment rule, as it is called, is linked to the polluter pays principle.[100] This principle can be referred to not just as grounds for an obligation to pay for after-treatment of environmental damage, it can also serve as grounds for

[98] In situations involving harm to human health, the option of damages liability for the owner of the plant shall apply, as per Chapter 32 of the Swedish Environmental Code (1998:808).
[99] See Chapter 2, Section 8 of the Swedish Environmental Code.
[100] See Chapter 2, Section 3 of the Swedish Environmental Code.

strict damages liability for the polluter. The obligation to provide after-treatment for harm and damage caused can be fulfilled by the responsible party, in this case SKB, taking real action to provide after-treatment or similar services, but the responsibility can also entail SKB paying for such measures to be undertaken by someone else.

Specific regulations on after-treatment can be found in Chapter 10 of the Swedish Environmental Code. *The after-treatment* rule applies to environmental damage to "land and water areas, ground water, buildings and structures that are so polluted that they may cause damage or detriment to human health or the environment."[101] The party responsible for after-treatment is the operator. This shall apply regardless of whether it ran operations or simply implemented a measure that contributed to pollution damage. Thus, the operator may be subject to an order entailing various requirements and issued by the responsible authority. The requirements can entail both investigation and after-treatment of harm. There are no further limits on this responsibility under the Swedish Environmental Code.

Ultimate responsibility lying with the state has been the subject of discussions in several contexts. However, there is no national legislation on the state having ultimate responsibility, neither in the Swedish Act on Nuclear Activities or the Swedish Environmental Code nor in any other legislation. However, both the Swedish Parliament and Government have stated on various occasions that the state has an overriding responsibility for spent nuclear fuel and nuclear waste.[102]

By ratifying the Joint Convention on the safety of spent fuel management and on the safety of radioactive waste management in 1997,[103] the Swedish state decreed that primary responsibility for safety in the management of spent nuclear fuel or radioactive waste would lie with the license holder for the facility that produced the waste (the reactor owner). The state has fulfilled its obligations under the convention by clarifying the reactor owner's

[101] See Chapter 10, Section 1 of the Swedish Environmental Code.
[102] See, for example, Gov. Bill 1980/81:90, appendix 1, p. 319; Gov. Bill 1983/84:60, p. 38; Gov. Bill 1997/98:145, p. 381; Gov. Bill 2005/06:183 and Parliamentary Committee on Industry and Trade reports 1988/89:NU31 and 1989/90:NU24. See SÖ 1999:60.
[103] See SÖ 1999:60.

responsibilities in legislation. If there is no such license holder, the responsibility lies with the state.

By establishing a Community framework for the responsible and safe management of spent nuclear fuel and radioactive waste, the European Council took a step towards clearer national responsibility.[104] The Directive came into force on 22 August 2011. Under the Directive, radioactive waste should, in general, be permanently disposed of in the Member State in which it was generated. The Directive is based on a number of general principles applicable to the management of spent nuclear fuel and radioactive waste, including the principle that all Member States are responsible for ensuring that any undue burden on future generations is avoided, and that the Member States must, therefore, ensure sufficient funding for the management of spent nuclear fuel and radioactive waste. Sweden has introduced the regulations featured in the Directive into Swedish legislation.

It can, therefore, be stated that responsibility after a final repository is permanently sealed is shared between several different parties.

Judgement of the Land and Environment Court on the state's ultimate responsibility

The Land and Environment Court at Nacka District Court, in its pronouncement to the Government on 23 January 2018, regarding SKB's application to establish a final repository for spent nuclear fuel, concluded that the licensee for the final repository is responsible after the permanent sealing of the final repository facility under the Swedish Environmental Code, and that this responsibility is not time-limited.

The basis for this conclusion is that there is a risk that a final repository could cause harm or damage to human health or the environment for 100,000 years or longer from the date of sealing. Some uncertainties will remain after sealing, even if the final repository has been constructed in accordance with the design criteria. For example, this can mean that under the Swedish

[104] Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste (Official Journal of the European Union L 199/48, 2 August 2011, p. 48, Celex 32011L0070).

Environmental Code the party in question could be held responsible for after-treatment of any environmental harm thousands of years after the sealing.

Thus, according to the Land and Environment Court, the issue arises as to whether the state should have ultimate responsibility for the final repository. This must be clarified in connection with any decision on whether operations are permissible under the Swedish Environmental Code.[105] The Swedish Parliament has made statements regarding the state's ultimate responsibility, but this has not led to any legislation.

Statutory provisions were proposed in the final report of Utredningen om en samordnad reglering på kärnteknik- och strålskyddsområdet ("The investigation into coordinated regulation of the nuclear technology and radiation safety sector" in Swedish), SOU 2011:18.[106] The Land and Environment Court questions the status of Parliament's statements, in relation to a permission judegement that has become res judicata. Will the licensee in the future be able to be released from their responsibility under a permission judgement, with reference to the state's ultimate responsibility, despite the fact this responsibility is not statutory?

The issue of who has responsibility for a final repository in the very long term is important as a matter of principle according to the Land and Environment Court. The Swedish Environmental Code includes a regulation stating that the licensee has long-term responsibility. Such a responsibility is consistent with the objectives of the Swedish Environmental Code under Chapter 1 Section 1. However, discussions between the parties show that there is a fundamental uncertainty as to what long-term actually means here.

The Land and Environment Court considers a final repository for spent nuclear fuel to be permissible only if the issue of who has very long term responsibility under the Swedish Environmental Code is clarified.

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[105] The Land and Environment Court at Nacka District Court 2018. Pronouncement 23 January 2018. Case No M 1333-11. Document appendix 842. Stockholm.
[106] Parliament's statements are recorded in the final report, see p. 495.

Continued investigations

The Government has recently launched an investigation with objectives including proposing a regulation on ultimate responsibility after the sealing of a final repository. The investigation will also analyse the pros and cons of separating responsibilities for nuclear safety and radiation safety from the long-term responsibility for decommissioning and disposal of waste.

This is unlikely to be the last investigation focusing on legislative issues.

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Legislation etc.

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SÖ 1999:60. The 1997 Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (the Nuclear Waste Convention).

Council Directive 2011/70/Euratom of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste (Official Journal of the European Union L 199/48, 2 August 2011, p. 48, Celex 32011L0070).

2.5 Stepwise licensing in accordance with the Swedish Act on Nuclear Activities

Introduction and objective

SKB's applications for a final repository for spent nuclear fuel are to be assessed through two processes, one in accordance with the Swedish Environmental Code and one in accordance with the Swedish Act on Nuclear Activities. If SKB is granted permission under both acts, the process will continue as per the Swedish Act on Nuclear Activities with a so-called stepwise licensing, as the project is complicated and set to be underway for a long time.

Stepwise licensing is used for nuclear technology facilities and is not a new process. What makes the case of a final repository for spent nuclear fuel special is that it is a new kind of facility with no similar constructions to refer to anywhere else in the world. (Finland has broken the ground in this area, but has a long way left to go).

There are uncertainties regarding how the assessment will progress. At the same time, stepwise licensing can be a way of managing some uncertainties, which may allow for better solutions through technical development.

The objective of this section is to discuss the issue of why stepwise licensing is required, what it entails, and what steps/stages it requires. In this stepwise licensing, safety analysis reports (SARs) will, as they are updated, form an important part of a safety analysis, which is also briefly described in this section. The section also highlights several definitions that require further clarification, such as trial operation.

Why is stepwise licensing in accordance with the Swedish Act on Nuclear Activities necessary?

Designing, constructing, and opening a final repository system (Clink and the final repository) for spent nuclear fuel – as with other nuclear technology facilities where ionising radiation exists – is a complex industrial process taking a long time to implement. Even if the KBS-3 method for final disposal of spent nuclear fuel has been tested for a long time under realistic circumstances at SKB's Äspö laboratory, problems may arise during the construction or establishment phases, which could lead to a need for other solutions. This applies not least to the crucial safety barriers – the copper canister and stabilising bentonite buffer – the reliability of which has been questioned by different experts during the introductory phase of the decision-making process, meaning that careful testing is required.

The design solutions set out during the application stage may need to be changed in the future. Both the Government's license terms and the authority's regulations must be formulated so as to support this kind of stepwise licensing.

SSM has, in its pronouncements, also recommended a stepwise licensing for the construction of the final repository. The ultimate issue is that of long-term protection of human health and the environment from damage and other harm as a result of ionising radiation.

What is meant by stepwise licensing – in principle

If the Government grants a license for a final repository system (Clink and the final repository), it is reasonable to assume that SSM, in connection with this, will decide on a number of terms for the license, including stepwise licensing of the safety of the final repository.[107] Here, it can be noted that SSM, notwithstanding the res judicata of the license under the Swedish Environmental Code, may prescribe more stringent or far-reaching measures, even if they were to deviate from the license conditions under the Swedish Environmental Code.[108]

In such situations, the license conditions would mean that the licensee, SKB – gradually as the establishment work progresses – would progressively produce preliminary SARs (see below), which would be submitted to SSM for approval. Each SAR submitted to SSM will undergo a safety review and must fulfil the requirements prescribed by SSM (SSMFS 2008:1 and 2008:21).[109] If SSM finds that

[107] Cf. Section 20 of the Swedish Ordinance on Nuclear Activities (1984:14).
[108] See Gov. Bill 2005/06:76, p. 29.
[109] The SAR is a key concept for nuclear technology facilities around the world. Overall, a SAR must show how the safety arrangements at the facility protect human health and the environment from radiological accidents. The report must reflect the facility as it is built, analysed and verified, as well as showing how the relevant design, functionality, organisation and operational requirements are fulfilled.

the requirements prescribed have been fulfilled, it will issue a decision stating that the SAR has been approved and the establishment work may continue. This process, when carried out for a final repository, will continue for approximately 70–80 years.

During this long time-frame, as stated it is reasonable to assume that research and technological developments will continue to take place, for example regarding the integrity of the copper canister and the stabilising capacity of the bentonite buffer. The system to prevent unintentional and intentional intrusion into the final repository – so-called physical protection – and to ensure that the spent nuclear fuel is not used for non-peaceful purposes – so-called nuclear safeguards – are other safety issues that must continually be taken into account. The design solutions set out during the application stage may need to be changed in the future. Problems may occur during the establishment phase that require improvements to the solutions used. This is why stepwise licensing is necessary. This kind of stepwise licensing of large nuclear technology facilities is also recommended by the IAEA, and is also in accordance with long-standing international practice.

Thus, based on progressively developed safety analyses, SSM will face a number of decisions where the authority at each stage will have to make a judgement on the long-term safety of the final repository and use continual testing to decide whether the KBS-3 method can be approved. Initially this will be more of an overview and conceptual in nature, which will then give way to a heightened degree of precision regarding how the relevant requirements for the facility and its operations have been fulfilled. Concerning the final repository, the conclusive SAR will be produced when the final repository is ready to be permanently sealed.

For a license, which comes with a number of conditions, to remain valid, the licensee must fulfil the license conditions.

The SAR will be based on a safety analysis

Safety after the sealing of a final repository will be maintained using a system of passive barriers. Each barrier is intended to, in one or multiple ways, contain, prevent or delay the spread of radioactive substances, either directly or indirectly by protecting other barriers in the barrier system.

Safety will be based on a safety analysis. This analysis must be able to reveal whether any of a range of potential shortcomings are present in a barrier (incl. the copper canister, bentonite buffer and the surrounding rock) and show that none of the barrier functions could lead to unacceptable risks of the spread of radioactive substances from the final repository. The safety of the final repository after sealing will be analysed quantitatively, primarily through the calculation of any spread of radioactive substances, and how they are distributed in time for a relevant selection of potential future scenarios.

The objective of the safety analysis includes showing that the risks associated with these scenarios are acceptable in relation to the requirements for the protection of human health and the environment. A further aim of the safety analysis should be to provide a basic understanding of how the final repository will function during different time periods, and to identify design-related and functional requirements for different parts of the final repository.

Under the regulations, a safety analysis must cover the entire timeframe the features of the barrier are required remain effective for, however at least 10,000 years. The safety analysis for the final repository for spent nuclear fuel may be required to cover scenarios that take into consideration major expected changes in the climate, primarily in the form of forthcoming glaciation. For example, one factor in particular that ought to be taken into account is the next complete glaciation cycle, which at present is forecast to last approximately 100,000 years.

The ultimate issue is that of long-term protection of human health and the environment from damage and other harm.

Which stages of the construction of the final repository should be considered steps in the stepwise licensing process

Different steps and definitions

At the time of writing, SSM had not yet precisely defined the different stages in connection with the construction of the final repository. Prior to its construction, an updated safety analysis is required, which will then need to be approved by SSM. However, there is no explicit definition in the Swedish Act on Nuclear Activities of what the construction of a nuclear technology facility entails. According to the travaux préparatoires, the concept refers to all measures taken to construct a nuclear technology facility in a given location. The concept of construction in this context primarily includes the construction of the buildings required for the work. Additionally, different kinds of groundwork also fall within the scope of construction. The breaking of the ground should, therefore, be considered the starting point for construction. Preparatory measures prior to this fall outside the scope of construction.[110]

Work on the bedrock down to repository depth could be seen as another stage in the construction process. The enlargement of each repository tunnel could potentially be regarded as a milestone or point of reference with specific approval by SSM, to show/confirm that SKB's design criteria, which form the basis for the SAR, have been fulfilled. In turn, this can lead to a gradual updating/supplementation of the facility description and documentation.

During the main hearing at the Land and Environment Court at Nacka District Court during autumn 2017, SSM presented the following, very broad descriptions of the different stages of the stepwise licensing under the Swedish Act on Nuclear Activities:[111]

4. When the application for Government permission is submitted (F-PSAR – preparatory preliminary safety analysis report) – based on the principle description of the facility.

[110] See Gov. Bill 1986/87:24, p. 6.
[111] The Land and Environment Court at Nacka District Court 2017. (Presentation by SSM). Prövningsförfarandet enligt lagen (1984:3) om kärnteknisk verksamhet ("The analysis procedure under the Swedish Act on Nuclear Activities (1984:3)" in Swedish). Case No M 1333-11. Document appendix 624. Stockholm.

5. Before a facility may be constructed (PSAR – preliminary safety analysis report) – based on the facility's planned design.
6. Before trial operation may be started (SAR[112], safety analysis report) – to reflect the facility as it is built.
7. Before the facility is then opened for standard operation – supplemented safety analysis report, taking into consideration experiences from the trial operation.
8. Before a final repository is sealed.

However, the description scarcely gives any more detailed information on the actual courses of events during the construction of the final repository, which could then be considered steps in a stepwise licensing process.

What is meant by trial operation and standard operation of the final repository are also issues requiring further consideration. This also applies to the meaning of the sealing of a repository tunnel. Does this refer to permanent sealing or perhaps a partial sealing of the spent nuclear fuel that has been placed in the tunnel? The issue should be assessed taking into consideration the Swedish Act on Nuclear Activities' concept "permanent sealing of the final repository", which according to the Act concerns a final point in time for the reactor owners' responsibility to safely decommission and dismantle facilities in which operations are no longer carried out.[113]

How the reactor owners' final responsibility should be weighed up against SKB's responsibility for the final repository facility as such has not been fully clarified in legislation either. See the section on the state's ultimate responsibility for final disposal of spent nuclear fuel (section 2.4).

Furthermore, according to Section 10a of the Swedish Act on Nuclear Activities, SKB must, at least once every ten years, carry out a new, systematic, full evaluation of safety and radiation safety aspects, and how these fulfil the requirements of the Swedish Act on Nuclear Activities, the Swedish Radiation Protection Act and the

[112] The concept refers, and is equivalent, to the Safety Analysis Report (SAR) as defined by the IAEA.
[113] See Chapter 10 Section 4 of the Swedish Act on Nuclear Activities (1984:3).

Swedish Environmental Code, as well as regulations set out and conditions decided upon with the support of these laws. In SSM's regulations[114], the wording is unclear as to whether the provisions on full evaluations also apply to a facility still under construction.

Many long deliberations remain – as well as potential supplements to the legislation – before conclusive (?) resolutions are found for the issues raised in this chapter.

Concluding reflections

The step-by-step, stepwise licensing process described in this section is based on different kinds of safety analysis, including:

- deterministic safety analyses, i.e. taking stock of all kinds of 'preliminary events' that could conceivably affect the facility
- a probabilistic safety analysis (PSA), i.e. a systematic survey of all imaginable breakdowns in operations that the potential 'preliminary events' could lead to, taking into account the different errors that can arise in the safety systems and during the construction of the facility
- a Human-Technology-Organisation analysis, i.e. an analysis of the significance of people and the organisation of work for the safety of the facility during its construction.

The safety analyses are necessarily based on assumptions, which in itself entails different degrees of uncertainty. Surveying and analysing systems using this methodology allows for the pinpointing of potential weak points in the system barriers. A certain degree of uncertainty in the predictions is unavoidable.

[114] See Chapter 4, Section 4 of the Swedish Radiation Safety Authority's regulations concerning safety in connection with the disposal of nuclear material and nuclear waste (SSMFS) 2008:1.

References

The Land and Environment Court at Nacka District Court 2017. (Presentation by SSM). The licensing procedure under the Swedish Act on Nuclear Activities (1984:3). Case No M 1333-11. Document appendix 624. Stockholm.

SSMFS 2008:1. *The Swedish Radiation Safety Authority's Regulations concerning Safety in Nuclear Facilities*. The Swedish Radiation Safety Authority.

SSMFS 2008:21. *The Swedish Radiation Safety Authority's regulations concerning safety in connection with the disposal of nuclear material and nuclear waste*. The Swedish Radiation Safety Authority.

Swedish Act on Nuclear Activities (1984:3).

Swedish Ordinance (1984:14) on Nuclear Activities.

Gov. Bill 2005/06:183, Finansieringen av kärnavfallets slutförvaring ("The financing of a final repository for nuclear waste" in Swedish).

Gov. Bill 1986/87:24, Om förbud mot nya kärnkraftsreaktorer m.m. ("On the prohibition of new nuclear reactors etc." in Swedish).

3 Technical and scientific uncertainty

On a number of occasions the Council has written about the uncertainties concerning the canister and rock, most recently in the *Review of the Swedish Nuclear Fuel and Waste Management Co's (SKB's) RD&D Programme 2016.*[115] Here, the Council provides some examples of uncertainties concerning these barriers. In terms of the canister, there is not as much research into the cast iron insert as there is for the copper liner. Amongst other elements, we would like to highlight some embrittlement mechanisms requiring further investigation.

3.1 Uncertainties regarding canisters and inserts

Introduction

We have opted to divide this section into two parts, written at two different levels, one a briefer description for general understanding, the other a technical description for experts. The objective here is to highlight to laypersons how important the stepwise licensing process is for continued research. At the same time, experts need information about the key gaps in terms of knowledge about the copper canister's properties and integrity, in particular its cast iron insert.

[115] The Swedish National Council for Nuclear Waste. 2017. SOU 2017:62 Review of the Swedish Nuclear Fuel and Waste Management Co's (SKB's) RD&D Programme 2016.

3.1.1 Summary description

The canister is the most important barrier for the KBS-3 repository's long-term safety. The canister will encase the spent nuclear fuel, and comprises a 50 mm thick copper liner. Inside the copper liner is a ductile cast iron (a type of cast iron) insert. As SKB has not carried out as much research into the cast iron insert as it has for the copper liner, on the whole the uncertainties are greater regarding the ductile cast iron insert.

The ductile cast iron insert

The ductile cast iron insert is load-carrying, i.e. it is intended to protect the canister from the pressure placed on it down at repository depth (approx. 500 metres). The load in question will come from water pressure, pressure from the swelling bentonite buffer, and from movements in the rock. It will take a long time before the spent nuclear fuel cools and the heat will affect the canister's characteristics over time.

The technical description below covers uncertainties concerning three chemical processes (embrittlement) that make the material more susceptible to break:

– hydrogen embrittlement
– static and dynamic strain aging (blue brittleness)
– radiation-induced embrittlement.

These processes can make the cast iron insert brittle, and if it fractures, it is possible that the copper liner will also break, badly damaging the canister. It is important that more and better knowledge is developed on these embrittlement mechanisms, and how, along with creep (deformation over time), they can affect the cast iron insert.

The canister must be able to withstand large loads that may arise as the result of earthquakes and under glacial conditions, for example. A 50 mm movement in the rock can cause deformation of the canister, and if the insert is brittle, it may fracture. The likelihood of major earthquakes that can cause this occurring in the proximity of the repository is low, but there is uncertainty stemming from the very long timeframes, at least 100,000 years, that the copper canisters will need to protect the surroundings from nuclear waste for.

The copper liner

The Council has, on a number of occasions, noted that there is uncertainty regarding the copper liner, most recently in the Review of the Swedish Nuclear Fuel and Waste Management Co's (SKB's) RD&D Programme 2016.[116]

Final remarks

In the Swedish National Council for Nuclear Waste's view, SKB's publications on the topic of the cast iron insert are limited.

For this reason, it is important that more knowledge on hydrogen embrittlement, blue brittleness and radiation-induced embrittlement is developed. SKB must also develop data that takes into consideration how embrittlement mechanisms and creep can affect the canister when occurring together. The limit values – for example for the hydrogen content of cast iron, which can affect the mechanical characteristics of the ductile cast iron insert – have not yet been specified.

This is an example of the areas where more research is required in order to minimise uncertainties. This research must be highlighted in SKB's forthcoming RD&D programme.

3.1.2 Technical description

The Swedish National Council for Nuclear Waste has previously questioned the durability of the canisters and highlighted areas where further knowledge is needed, including creep, corrosion, the formation and impact of hydrogen, the damage tolerance of the cast iron inserts, and the reliability of non-destructive testing in terms of

[116] Most recently in the Swedish National Council for Nuclear Waste. 2017. SOU 2017:62 Review of the Swedish Nuclear Fuel and Waste Management Co's (SKB's) RD&D Programme 2016.

revealing small but significant defects.[117] As SKB has not carried out as much research into the cast iron inserts, there are, in general, greater uncertainties here than regarding the copper liner. This applies to the mechanical characteristics, microstructure and chemical composition. Variations may occur when the inserts are cast, affecting the quality of the inserts in terms of ductility (elongation) and fracture toughness.

The objective of this section is to highlight uncertainties primarily concerning the cast iron inserts and their characteristics in the long term. These are uncertainties that must be managed at the very least through the stepwise licensing under the Swedish Act on Nuclear Activities. In terms of cast iron inserts, three types of embrittlement, amongst other things, are discussed in the text below:

1. When subject to gamma and neutron radiation, the copper content (an impurity in iron) in the insert's cast iron affects its mechanical characteristics (so-called radiation-induced embrittlement).
2. The impact of the hydrogen gas formed on all of the canister materials (so-called hydrogen embrittlement) must be investigated more thoroughly.
3. Another embrittlement mechanism seen in cast iron that has not yet been studied in sufficient depth is static and dynamic strain aging (so-called blue brittleness).

Design analysis and requirements for cast iron inserts

The cast iron insert is the canister's load-carrying element, thus there are high requirements placed on its durability. The insert is manufactured from ferritic ductile cast iron[118], which is a form of cast iron. Ductile cast iron[119] is a suitable material and a common choice for large structures such as the canister insert. The ductile cast iron's mechanical characteristics are primarily due to the

[117] The Swedish National Council for Nuclear Waste. 2017.
[118] EN 1563 grade EN-GJS-400-15U.
[119] Eng. ductile cast iron, DCI.

microstructure in its matrix (ferrite and pearlite content); the shape, size and distribution of the graphite; slag inclusions and porosity/casting defects. All characteristics are controlled by the chemical composition, process controls, and heat treatment.[120]

The maximum temperature in the copper canister is reached in the middle of the fuel, i.e. at the centre of the fuel element (approx. 230°C, maximum permitted temperature 300°C).[121] Due to the cast iron's high conductivity, the temperature of the cast iron insert is lower and SKB does not take the temperature gradient into consideration in the thermal analysis. The maximum temperature in the cast iron insert is up to 60°C higher than that in the copper liner.[122] The maximum temperature on the copper canister surface (approx. 90°C) and on inner surface of the buffer (approx. 80°C) will be reached after approximately 10 years. The thermal development in the copper canister and the increased temperature will affect the processes in the canister for a relatively short period of time, i.e. a few thousand years. The temperature in the copper liner will remain above room temperature for approximately 7,000 years after being deposited, after which the temperature will fall slowly to the temperature of the surrounding rock. During the early period of elevated temperatures (the first 1,000 years), different ageing mechanisms (both static and dynamic strain aging, so-called blue brittleness, see below for more information) can impact upon the cast iron, which at a later point may also be of major significance for the durability of the cast iron insert at lower temperatures.

When subject to gamma and neutron radiation, the copper content in the insert's cast iron affects its mechanical characteristics (**radiation-induced embrittlement**). Radiation-induced precipitation of copper in the cast iron can cause embrittlement, and the characteristics of the cast iron may worsen in terms of stable ductile crack growth (the material becomes brittle). In order to be

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120 Raiko et al. 2010. Design analysis report for the canister; SKB. 2009. Design premises for a KBS-3V repository based on results from the safety assessment SR-Can and some subsequent analyses; SKB. 2010. Design, production and initial state of the canister; Mourujärvi et al. 2009. "Influence of chunky graphite on mechanical and fatigue properties of heavy-section cast iron. Fatigue & Fracture of Engineering Materials & Structures." p. 32.; Wallin. 2014. "Equivalent Charpy-V impact criteria for nodular cast iron."; Hutter. et al. 2015. "Micromechanisms of fracture in nodular cast iron: From experimental findings towards modeling strategies – A review"; Raiko. 2013. Canister design 2012.

121 Raiko. 2013.

122 Raiko. 2013.

able to impose requirements regarding the maximum copper content of the cast iron insert, thereby reducing uncertainty in terms of embrittlement, research on radiation-induced embrittlement of cast iron shall continue.

There are both internal and external sources of hydrogen in the canister that can cause **hydrogen embrittlement**. In accordance with the design conditions for the canister, the amount of water left in each canister must be less than 600 g.[123] It is plausible that oxygen-free iron corrosion can occur, producing hydrogen gas. The effect of this hydrogen gas on all canister materials, including cast iron, shall be investigated. At the same time, the stress, hydrogen content and temperature can also increase the risk of hydrogen embrittlement and creep. In terms of the insert, there are relatively few research reports on hydrogen embrittlement of ductile cast iron with a ferritic matrix.[124] The effect of even low pearlite content[125] has not yet been studied. The hydrogen content of the cast iron is much higher than in carbon steel, for example, even with a high pearlite content. Research into ductile cast iron has shown that hydrogen accumulates not only on graphite/ matrix interfaces, but also within the graphite nodules. In ductile cast iron, the porosity impacts upon both hydrogen content and diffusivity. The ductility of ductile cast iron is affected drastically by hydrogen and brittle, quasi-cleavage fracture occurs around the graphite nodules. The separation of graphite from the matrix initially takes place before the initiation of cracks, and the susceptibility to brittle crack growth increases if the strain rate decreases. It is important that research is started into this, as the current basis of knowledge on the topic is insufficient.

An embrittlement mechanism within the ductile cast iron that has not yet been studied at all, and which must be taken into consideration, is static and dynamic strain aging (**blue brittleness**). The matrix in ductile cast iron, where plasticity takes place, is ferritic, similarly to electric steel, however ductile cast iron has no sharp yield point.[126] The reason for this may be that plastic flow of the graphite nodules begins on a continual basis under the proof

[123] SKB. 2010.
[124] Takai et al. 2002. “Visualization of the hydrogen desorption process from ferrite, pearlite, and graphite by secondary ion mass spectrometry”; Matsunaga et al. 2014. “Ductility loss in ductile cast iron with internal hydrogen”; Matsuo. 2017. “The effect of pearlite on the hydrogen-induced ductility loss in ductile cast irons.”
[125] A two-phased, lamellar structure formed of alternating ferrite and cementite layers (Fe3C).
[126] Hutter et al. 2015; Pihlajamäki. 2017.

stress, meaning that the material does not show a sharp yield point, even if the dynamic strain aging of the cast iron is qualitatively similar to that of standard structural steel. It is important to understand how strain aging impacts upon the ductility and toughness of the ductile cast iron insert. Strain aging is a hardening and embrittlement mechanism that takes place in carbon steel and cast iron under specific combinations of plastic strain and temperature conditions. If embrittlement occurs after deformation, it is called static strain aging. If the embrittlement occurs at the same time as the deformation, it is called dynamic strain aging. The phenomenon occurs within the temperature range of 50–250°C, where the materials' specific free carbon and nitrogen contents are decisive for the embrittlement. Carbon and nitrogen atoms diffuse and collect around dislocations and grain boundaries, causing embrittlement in iron.[127]

The cast iron insert will be placed under a load for a long time, which may lead to creep in the cast iron. Creep in the cast iron can be affected by the complex geometry in the inner parts of the insert, as well as the hydrogen content and residual stress from casting. There are currently only limited results from creep testing, and these have been used to rule out creep as a degradation mechanism in the cast iron insert in repository conditions. It is important that SKB continues to carry out testing of creep in cast iron.

The canister must be able to withstand loads during, for example, earthquakes and glacial conditions. It must be able to withstand a maximal isostatic loading of 45 MPa, which is the sum of the maximum swelling pressure of the bentonite and the maximum ground water pressure. The load-bearing features of the insert in terms of isostatic loading also encompass asymmetrical loads as a result of uneven bentonite swelling. The cast iron insert must be able to withstand a maximum external load, as a result of uneven bentonite swelling, of 15 MPa, at a heightened temperature of approximately 125°C, for the first 1,000 years.

The canister must be able to withstand shear stresses that occur when the fractures that intercept the deposit holes are exposed to secondary shear movements following major earthquakes in the vicinity of the final repository. The canister must be intact even after a 50 mm shear movement with a speed of 1 m/s, for all positions and

[127] Honeycombe and Bhadeshia. 1995. Steels, Microstructure and Properties.

angles of the shear in the deposit hole, and at all relevant temperatures down to 0°C.[128] Shear movements may occur at any point during the deposition period, but are primarily expected to occur during early and late glacial periods.

The likelihood of a major earthquake occurring in the vicinity of the final repository is low, and therefore shear movements of 50 mm at the site of the deposit hole are rare. Deposit locations intercepted by a fracture that runs across the entire circumference of the tunnel must, therefore, be avoided according to SKB. In order to identify the shortest fracture in the bedrock in the vicinity of the deposit holes, it is important to investigate and measure the mechanical characteristics of bedrock fractures and demonstrate whether 50 mm shear movements can occur.[129] If there are fractures across the tunnels, one or more canisters may be subject to shear of 50 mm or more as a result of an earthquake, even within a 1,000-year timeframe, thus potential damage to canisters cannot be fully ruled out.

Summary regarding the inserts and conclusions

The cast iron inserts in the canister must be able to withstand the load combinations occurring in the final repository without plasticising, with the exception of major shear loads. The canister's cast iron insert may be exposed to asymmetrical loads due to uneven water saturation in the buffer and isostatic loads after complete saturation of the buffer, without plasticity in the insert occurring. Shear loads from earthquake-induced shear movements may occur in bedrock fractures that intercept the deposit hole throughout the entire final repository period. These shear movements may cause significant plasticity of the cast iron inserts. A 50 mm shear movement can lead to plastic deformation in the cast iron inserts of 1–2.5%.[130] There are major uncertainties concerning the integrity of the canister in terms of the cast iron's ductility and fracture toughness when combined with the accepted defect size. Resistance

[128] Raiko et al. 2010; SKB. 2009. Design premises for a KBS-3V repository based on results from the safety assessment SR-Can and some subsequent analyses; SKB. 2010; Raiko. 2013.
[129] Uotinen. 2018. Prediction of stress-driven rock mass damage in spent nuclear fuel repositories in hard crystalline rock and in deep underground mines.
[130] Raiko et al. 2010; SKB. 2009; SKB. 2010.

to a maximal isostatic loading can also be drastically affected if the canister is first exposed to plasticising shear movements (static strain aging).

The mechanical degradation mechanisms analysed by SKB for cast iron inserts in deposition conditions only include ductile collapse (buckling) through the initiation of cracks, and stable ductile crack growth, when the point of maximum load has been reached.[131] SKB has excluded brittle cleavage fractures as they, taking a non-conservative stance, consider cast iron to be a ductile material in all expected conditions in the repository, and throughout the entire temperature range.[132]

It is known that ductile cast iron has a ductile-to-brittle transition temperature[133] in low temperature ranges and increased strain rates.[134] SKB has only carried out materials testing at temperatures from 0°C to room temperature, and not in the deformation aging range of 50–250°C. Several tests have been carried out with high strain rates, and based on these, SKB has reached the conclusion that brittle cleavage fracture of the cast iron insert is not possible in the final repository conditions. At elevated temperatures it is possible that there will be a drastic reduction in total elongation at fracture (the ductility of the material) and fracture toughness. When analysing the cast iron insert's durability, the loads must be specified and elevated temperature also taken into consideration. Temperature-dependant data on the mechanical characteristics, such as ductility and fracture toughness of the cast iron inserts, is lacking, which means that there are major uncertainties remaining. If the load-bearing cast iron inserts fracture through a brittle fracture mechanism, it is possible that the copper liner will also fracture, damaging and breaking the canister.

There is no data providing an overview of the effects of blue brittleness, radiation-induced embrittlement, hydrogen embrittlement and creep together. The ductile cast iron inserts are prone to both static and dynamic strain aging within the temperature range of the canister, both during and after a plasticising shear movement in the rock. The residual stress in the insert may also affect this process. Hydrogen affects the mechanical characteristics

[131] Raiko et al. 2010; SKB. 2009; SKB. 2010; Raiko, 2013.
[132] Raiko et al. 2010.
[133] Eng. ductile-to-brittle transition temperature.
[134] Hutter et al. 2015.

of the ductile cast iron insert, yet thus far SKB has not specified the permitted hydrogen content limits.

The critical defect size of the cast iron insert (weight 13.6 tonnes) is only 4.5 mm deep to withstand a shear movement of 50 mm, which places significant requirements on manufacturing and non-destructive testing.[135] The intended methods for quality control of both the cast iron insert and the copper liner are still at the preliminary stage. Therefore, the canister design prerequisites require a renewed design and defect analysis based on the current design prerequisites. The requirements placed on the canister's mechanical characteristics and permitted defect size are currently deterministic. The acceptable defect size varies in different parts of the cast iron insert. Despite the fact the material characteristics ought to be homogenous, unavoidable variations in the cast iron insert's material characteristics lead to different permitted defect sizes, based on the analysis of damage tolerance, and these may lie towards the lower end of the detection capacities of the non-destructive testing methods used.

SKB has expressed a desire to relax the requirements on elongation at fracture in the cast iron insert (>12 %), tensile yield strength (>240 MPa) and fracture toughness (ductile fracture) $K_{Ic}>78\ MPa(m)^{1/2}$ (fracture toughness obtained at 2 mm stable crack growth in a test piece).[136] This applies to the middle of the insert, which will then lead to different requirements for the mechanical characteristics and defect size of different parts of the insert. If the requirements and acceptance criteria for mechanical characteristics and defect size of the ductile cast iron are relaxed, primarily for the central parts of the insert, where the characteristics vary and are worse due to the microstructure/graphite distribution, potential defects and slag inclusions, new damage tolerance analyses will have to be carried out for the different load combinations. SKB would also like to relax the requirements for non-destructive testing.[137] If different parts of the canister's insert (base plate, top and between the channels) do not need to be inspected, verification of this must be provided through production and quality assurance.

[135] Raiko et al.; SKB. 2009; SKB. 2010.
[136] SKB. 2016. RD&D Programme 2016. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste.
[137] SKB. 2016.

The copper liner – uncertainties in mechanical characteristics and damage tolerance

There are still uncertainties remaining regarding the analysis of the copper canister's design. In terms of the copper liner, a validated model of how copper creep occurs has yet to be provided. The model shall be based on the exact mechanism and show how the integrity of the copper liner can be maintained at different loads. Thus, more studies of the creep mechanisms under different mechanical loads are required. In order to improve the modelling of creep, allowing for more thorough assessments of the canister's durability, mechanistic understanding of how phosphorous alloying provides favourable creep characteristics in copper is needed. Further understanding is required in order to be able to establish the necessary requirements concerning the hydrogen, oxygen, sulfur and phosphorous contents of the copper.

Final remarks

Research to increase knowledge on the aforementioned areas shall continue, in order to fulfil the specifications set out and to ensure quality requirements are included in the production process, so that conclusions can be drawn on the long-term safety of the repository. More work is required to confirm whether the variation in the durability characteristics of the cast iron insert is acceptable, taking into consideration all embrittlement mechanisms, and whether the results show that the testing has been carried out on a material with the worst conceivable characteristics. Acceptance criteria for different manufacturing defects shall also be developed. Uncertainties regarding the canister, not least its insert, form one example of how important the stepwise licensing is for ensuring more detailed reference designs in the applications.

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3.2 Uncertainties, interpretations and models of the bedrock in Forsmark

Introduction

After the conclusion of location investigations, in June 2009 SKB stated that it considered the conditions in Forsmark to provide the best preconditions for long-term safety, not least due to the nature of the bedrock. In order to characterise the rock, geological and geophysical investigations at the surface have been combined with different studies of drill core samples and measurements in the drill hole. The results of the investigations have been summarised in site description models by SKB. As the bedrock is not composed of a homogenous material, the models form a simplification that does not entirely correspond with the actual complexities the bedrock exhibits. There are different kinds of model: some show the present circumstances, others show different aspects of the geological development, whilst others reflect different future scenarios. It should be possible to validate the models that reflect ongoing processes or processes that can be simulated in a laboratory.

The objective of this chapter is to highlight some examples of what is known and what is less-well known about the bedrock in the Forsmark area, and why it is difficult to model geological development with a high degree of certainty. The models aim to reflect the reality, but they are always marred by uncertainties, as even in the best case scenario they constitute an estimate of the natural processes or circumstances. The models are also dependent on simplifications and how boundary conditions, which are specially imposed conditions, are formulated in the detailed calculations. In this section, we will first provide background information on what is known about the bedrock in Forsmark, followed by uncertainties concerning rock stress and larger earthquakes in the future. Afterwards, brief descriptions of some different kinds of models are provided.

The bedrock in the Forsmark area

The Svecokarelian bedrock domain

The bedrock in Forsmark is composed of what is generally referred to as stable basement, or more specifically, older crystalline rocks, which belong to the Svecokarelian bedrock domain that constitute larger parts of Sweden and southwest Finland. Broadly speaking, knowledge about the formation of the Svecokarelian bedrock, i.e. the Svecokarelian orogeny, and the later geological developments is good, but the knowledge is based on information that is geographically unevenly distributed – some areas are well surveyed, whilst the collected data from other areas is sometimes sparse, difficult to interpret, or based on outdated methods. The level of detail concerning the bedrock's characteristics and nature also varies significantly.

The level of detail in which the geology has been studied in Forsmark is unparalleled elsewhere in Sweden, yet there are uncertainties in the evaluation of the bedrock's characteristics that could potentially be of significance for the long-term safety and integrity of the planned final repository for spent nuclear fuel. Most often these uncertainties are related in one way or another to the transport of the water in the bedrock.

A broad overview of the development of the bedrock in the Forsmark area

The geological development of the Forsmark area and the relationship with the bedrock formation processes in this Svecokarelian domain is well known, not least due to SKB's site investigations.

1.89 and 1.80 billion years ago (Gy)

The bedrock in Forsmark was formed between 1.89 and 1.85 Gy (billion years) ago and underwent ductile deformation and metamorphism during the mountain forming processes referred to as the Svecokarelian orogeny, approximately between 1.9 and 1.8 Gy ago. The first phase of ductile deformation and metamorphism caused recrystallisation of the rock volume that preceded intrusion of the youngest, 1.85 billion year old rock constituting the youngest granites in the Forsmark area.[138] After this, the ductile deformation was focused to shear zones and carried on until approximately 1.80 Gy.

1.80 to 0.9 Gy

Through cooling and a gradual up-lift to shallower levels, the bedrock changed from deformed in a ductile to an elastic manner. The rock became stiffer, and when deformation took place, brittle fracturing occurred.[139] Movements along the brittle zones are coupled with distant tectonic processes that began 1.80 Gy ago, and continued when the bedrock affected by extension at 1.7–1.6 Gy ago, and when the Sveconorwegian mountain range formatted (1.0–0.9 Gy ago), which transformed the bedrock in southwest Sweden and southern Norway.

500 to 40 million years ago

The fractures already formed in Forsmark were probably reactivated during the formation of the Swedish–Norwegian mountain range known as the Scandinavian Caledonides (500 million years ago), the formation of younger mountain ranges in Europe, and opening of North Atlantic approximately 40 million years ago.[140] Movements along the fractures can also be linked to the loading and unloading of sedimentary rocks and glaciers.

The oldest of the brittle fractures (1.8–1.6 billion years old), which are exposed at the surface today, were formed at relatively deep depths, and minerals that have precipitated in these fractures shows that the temperature was at a few hundred degrees Celsius, and that water was present. Fractures related to the formation of the Sveconorwegian mountain range (1.0–0.9 Gy ago) are also healed by minerals, but these were formed at lower temperatures and closer to

[138] Hermansson et al. 2008. "Migratory tectonic switching, western Svecofennian orogen, central Sweden: Constraints from U/Pb zircon and titanite geochronology."
[139] Saintot et al. 2011. "Brittle tectonic evolution and paleostress field reconstruction in the southwestern part of the Fennoscandian Shield, Forsmark, Sweden."
[140] Saintot et al. 2011.

the surface.[141] Some fractures host later mineral that have dated to 300 million years.

Fractures that are not healed by mineral, so-called open fractures, cannot be dated, but may be hundreds of millions of years old. This fracture type, along with some of the healed fractures, forms zones of weakness in the rock, and tends to be reactivated when rock stresses exceed what the rock strength.

The occurrence of larger fracture zones around relatively fracture-free rock may, therefore, be a safety valve, and of significance for the long term safety, as any movements caused by an earthquake will be focused there, and as the deposit holes are required to be free of visible fractures. Despite this, there is a risk that the fractures could progagate and form new fracture networks in formerly intact rock.

Rock stresses in Forsmark

Rock stresses are caused by loading, and they increase as the depths increase. Stresses are caused by both vertical and horizontal forces. The vertical loading is caused by the weight of the overburden rock. The horizontal stress is more complex, and is ultimately attributed to plate tectonic forces linked to opening of the Atlantic.[142]

The rock stresses at Forsmark have been assessed using different kinds of direct measurements (overcoring, hydraulic fracturing and hydraulic tests in existing fractures) in drilled holes and through indirect observations of drill holes, drill cores and laboratory tests.

Regardless of the method, these show that the largest stress direction (referred to as σ1 or σH, where σ is stress and H stands for horizontal) has a NNW-SSE orientation, which corresponds well with the stress field caused by the ongoing spread of the north Atlantic (so-called ridge push). Information from seismic data and rock stress measurements in other parts of north-west Europe shows the same orientation of σ1.

[141] Sandström et al. 2009. "Brittle tectonothermal evolution in the Forsmark area, central Fennoscandian Shield, recorded by paragenesis, orientation and 40Ar/39Ar geochronology of fracture minerals."
[142] SKB. 2011. Environmental Impact Assessment. Interim storage, encapsulation and final disposal of spent nuclear fuel, section 7.2.3.2 Rock stresses.

However, the magnitude of the horizontal rock stress vectors in Forsmark is poorly defined, as the measurement results vary significantly depending on the method used. This can be partially explained by the fact that hydraulic methods are not optimised for measurements in vertical drill holes with a stress field equivalent to $\sigma H > \sigma h > \sigma v$ (where σH stands for the greatest horizontal stress direction, σh for the smallest horizontal stress direction and σv for the vertical stress direction), i.e. the smallest (σv) of the three stress directions is vertical.[143]

The results from the overcoring method are not considered reliable either. They are higher than what numerical analysis methods show[144] and close to double that of the hydraulic methods. The fluctuating values during the measurements indicate that the strain was influenced by the equipment and this has been attributed to the heat generation during the overcoring.

The fact that knowledge on the magnitude of the rock stresses in Forsmark is uncertain may be of significance for the safety analysis, as the magnitude of the rock stresses affects rock mechanical and hydrogeological models. High rock stress, as shown by some of the measurements in Forsmark, would, for example, counteract formation of fractures in the rock in a permafrost scenario where the pressure from the frozen bentonite increases, however, if the rock stresses are lower, fracturing could occur.[145]

Rock stresses and earthquakes

An earthquake causes tremors known as seismic activity, and occurs when the accumulated rock stress exceeds the strength of the bedrock. An earthquake can cause the rock to fracture or generate movements along existing fracture planes, so-called faults. If a larger fracture were formed, or faulting occurred along older fractures due to a large earthquake, the buffer and canisters could be damaged, entailing a risk of radionuclides spreading beyond the deposit (see section 3.1). The copper canisters in the KBS-3 method form a

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[143] Doe et al. 2006. "In-situ stress measurements in exploratory boreholes."
[144] Martin. 2007. Quantifying in situ stress magnitudes and orientations for Forsmark, Forsmark stage 2.2.
[145] Stephansson. 2010. "Viewpoints on selected parts of SKB's RD& D Programme 2010."

mechanical barrier between the waste and the bentonite buffer, and according to SKB should be able to withstand a 50 mm displacement.[146] This kind of displacement could occur if the canister were placed in a deposit hole with a continuous fracture exposed to a movement in the event of a major earthquake. The safety distance to major fracture zones is, therefore, important, as is the requirement that deposit holes featuring crosscutting fractures is discarded.

Seismic activity in the past, present and future

The Nordic countries are located in a stable bedrock area with low seismic activity, far from the boundaries between tectonic plates where the plates are pulling apart or colliding – typically resulting in high earthquake frequencies. Despite the stable location, there is a horizontal stress field in the bedrock. In Sweden, this is related to the spreading of the Atlantic, combined with a readjustment of the earth's crust following the deglaciation of the last inland ice in the area, and on average this triggers two earthquakes a year with magnitudes exceeding M3. Lower magnitude earthquakes occur daily, but since 1375, only two earthquakes with a magnitude of over 5 have been registered in Sweden. Almost 650 years may sound like a long time, but it constitutes only a fraction of the time the repository must remain safe and intact. Thus, over a longer timeframe there are traces of major earthquakes in the form of faults where larger movements took place during deglaciation between 11,000 and 9,500 years ago.[147] These faults have been documented in Norrland, and there are indications that they also exist in the central parts of the Sweden.[148] However, the prevalence of late- to post-glacial faults and other formations formed through seismic activity further south is still the topic of some debate. The argument for major earthquakes occurring in this area[149] has been met with

[146] The Swedish National Council for Nuclear Waste. 2016. SOU 2016:16 Nuclear Waste State-of-the-Art Report 2016.Risks, uncertainties and future challenges.
[147] Lund et al. 2017. Review of paleo-, historical and current seismicity in Sweden and surrounding areas with implications for the seismic analysis underlying SKI report 92:3.
[148] Lund et al. 2017.
[149] Mörner. 2003. "Paleoseismicity of Sweden, a Novel Paradigm."; Mörner. 2004. "Active faults and paleoseismicity in Fennoscandia, especially Sweden. Primary structures and

counter-arguments where these formations is instead explained by glaciogeological activity.[150] However, there is consensus that seismic activity, of more moderate magnitudes, did occur in the southern half of Sweden during the late- to post-glacial period.

Earthquakes of a certain magnitude occur with some regularity and in Sweden, and statistically an earthquake of a magnitude of 5 occurs every hundred years, whilst a tremor of a magnitude of 6 takes place every thousand years.[151] However, calculating where these will take place is challenging, as equations are partially based on the frequency and magnitude of previously recorded earthquakes within a certain area, and instrumental measurements have only been possible for just over 100 years, which is a relatively short period of time. It has also been shown that earthquakes can occur in areas that have been seismically inactive for very long period, such as the 4.8 earthquake in Kaliningrad in 2014. Only a few earthquakes, and of low magnitude (<3) have been registered in Forsmark and the surrounding area during the period of instrumental measurements.

This means that calculations of how many large earthquakes will occur in Sweden, let alone the Forsmark area, over the next 100,000-year period are very uncertain[152] and would be classified as an 'uncertainty' as per figure 1.1 in section 1.1.

Models – conceptual, structural and numerical models

The primary aim of modelling is to understand processes, with the objective of reducing uncertainties, with topics covering anything from a weather forecast to groundwater transportation, or how a mountain range is formed.

Many aspects that affect the rock as a barrier, be it the fracture network in the rock or variations in the groundwater composition

secondary effects."; Jakobsson et al. 2014. "Major earthquake at the Pleistocene-Holocene transition in Lake Vättern, Southern Sweden."

150 36 Largerbäck et al. 2005. Forsmark site investigation: Searching for evidence of late- or post- glacial faulting in the Forsmark region, results from 2002–2004; Lagerbäck and Sund. 2008. "Early Holocene faulting and paleoseismicity in northern Sweden."; Smith et al. 2014. "Surficial geology indicates early Holocene faulting and seismicity, central Sweden."; Mikko et al. 2015. LiDAR-derived inventory of post-glacial fault scarps in Sweden; Lund et al. 2017.

151 Böðvarsson et al. 2006. Earthquake activity in Sweden. Study in connection with a proposed nuclear waste repository in Forsmark or Oskarshamn.

152 Böðvarsson et al. 2006

in time and space, have been modelled in different ways, and the importance of different kinds of models and modelling cannot be emphasised and is clearly reflected in SKB's research programme, the RD&D Programme 2016, in which a large range of different types of modelling are described.[153]

There are different kinds of models, and they can be based on knowledge of when, where and how different processes were active, and can be illustrated schematically. They can even consist of laboratory models on different scales, from 1:1 to both upscaled and downscaled versions, where the processes can be studied in controlled circumstances. In addition to this there are different scenarios included in the models, providing various future climate developments, effects of earthquakes with different magnitudes, and fracture propagation to name just a few.

Conceptual models

Models that show how something works or describe the process of an event based on known parameters, which can then be put into a larger context, are usually termed conceptual models. They show how different parameters develop over time. For example, there are models of how the landscape and sea levels changed when the last glacier withdrew, and of how the formation and development of the approximately 2 billion year old Svecokarelian mountain range occurred.

Structural models

Another category of models is structural models, which are produced to visualise the distribution of different entities in three dimensions, in situations that cannot be directly observed, e.g. the distribution of rock types with depth and spatial distribution of larger fracture systems and deformation zones.

[153] SKB. 2016. RD&D Programme 2016. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste.

Numerical models

In order to be able to understand more complex geological processes and how different parameters interact, so-called numerical models are developed, which simulate different scenarios based on data and calculations provided. Numerical models are based on mathematical models, however, to solve these often complex equations, different numerical methods are required to break them down into smaller elements. The models are generated through different kinds of computer simulations. Thanks to the development of more powerful computers, the amount and complexity of numerical modelling carried out has increased exponentially. Despite the rapid developed of computer power, the models are a simplification of the natural systems they are based on. This natural complexity poses a challenge, as different parameters that are not necessarily independent of each other are modelled separately, these could be water biogeochemical, thermal, mechanical and hydrological development, or in other instances the irregular shape and surface of discrete fractures are simplified into symmetrical, well-defined mathematical objects.

Uncertainties

Despite the fact there is a high level of knowledge on geology and subjects related to the bedrock in the Forsmark area available, and the collected data can, in many respects, be explained either using direct observations or with different kinds of models, there are still some remaining uncertainties. The reliability of the models is dependent on the input data and the simplifications the models are based on, and modelling is, at the end of the day, just a way of simulating reality. Furthermore, some models have been subject to scrutiny, not least regarding the significance of the discrete fracture network for long-term safety, and how this ought to be modelled, as well as the significance of the late- to post-glacial seismic activity in a modelled future scenario.[154]

[154] The Swedish National Council for Nuclear Waste. 2017. SOU 2017:62 Review of the Swedish Nuclear Fuel and Waste Management Co's (SKB's) RD&D Programme 2016, p. 26 "Modelling of discrete fracture networks (DFNs)".

Validating the models, i.e. ensuring that the results achieved reflect the natural processes, regardless of which model and including future developments, is not a simple task, and always entails some degree of uncertainty. The models that can be compared directly with measurement data and observations of what is being modelled, e.g. which major water-conducting fracture systems are connected to each other, can be validated, whilst models based on presumptions, limited data or long timeframes, are difficult or impossible to validate.

It is impossible to fully eliminate all uncertainties regarding the nature of bedrock and how groundwater will behave over the next hundred thousand years. The modelling shows probable, but simplified scenarios that decisions on constructing a nuclear waste repository, regardless of location or method, having to be made sooner or later, despite remaining uncertainties and the knowledge that there are still various types of unknowns.

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Smith, C.A., Sundh, M. and Mikko, H. 2014. "Surficial geology indicates early Holocene faulting and seismicity, central Sweden." *International Journal of Earth Sciences* 103, p. 1711–1724. doi:10.1007/s00531-014-1025-6

Stephansson, O. 2010. "Viewpoints on selected parts of SKB's RD&D Programme 2010" Appendix to The Swedish National Council for Nuclear Waste. 2011. SOU 2011:50 *Review of the Swedish Nuclear Fuel and Waste Management Co's (SKB's) RD&D Programme 2010.* The Swedish National Council for Nuclear Waste. Stockholm: Fritzes.

3.3 Safe limits? On doses and risk

Introduction

A risk associated with a final repository for spent nuclear fuel is that the technical barriers could leak and radioactive substances (radionuclides) could then be released and transported through the 'natural barrier' of rock, up to a level where they could affect humans and the environment. The technical barriers, the canister and bentonite, must prevent the radionuclides from leaking out, and if they do leak, delay their progress to the surface.

The radiation emitted by radioactive substances is ionising, which means that it causes chemical changes in the irradiated material. In terms of ionising radiation, the absorbed dose is a fundamental concept. The dose describes how much energy is absorbed by the irradiated object.[155] In order to be able to protect people and the environment from the harmful effects of radiation, exposure limit values are determined. In terms of limit values for a final repository for spent nuclear fuel, the regulations set out under SSMFS 2008:37 are key.[156] The regulations set out maximum annual acceptable risk of harmful effects, including for the longer term.

> SSMFS 2008:37
> **Section 5** 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.
>
> The probability of harmful effects as a result of a radiation dose shall be calculated using the probability coefficients provided by Publication 60, 1990 of the International Commission on Radiological Protection.

[155] More information on the impact of ionising radiation on cells can be found in sources such as The Swedish National Council for Nuclear Waste. 2016. SOU 2016:16 Nuclear Waste State-of-the-Art Report 2016. Risks, uncertainties and future challenges.
[156] SSM. 2008. SSMFS 2008:37. The Swedish Radiation Safety Authority's Regulations Concerning the Protection of Human Health and the Environment in Connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste.

The wording of this paragraph also indirectly means that SSM places a limit value on the radiation dose for the population groups concerned. Simply put: only one in a million each year may suffer harmful effects. This covers those most exposed and whom live closest to the repository, and in particular those running agricultural operations on the land closest to the repository. This scenario applies to the period after the sealing of the repository, and not during its construction and operation.

The 1990 Recommendations of the International Commission on Radiological Protection (ICRP 60)[157] includes presumptions and calculations that provide the basis for the limit value for the radiation dose that can be calculated based on SSMFS 2008:37. The evaluation in ICRP 60 of the risk of harmful effects (i.e. the likelihood of developing cancer as a result of the radiation) is, therefore, marred by significant uncertainties. The background of and uncertainties in the ICRP's risk estimation have been covered extensively in the Council's State-of-the-Art Report for 2016.[158] The objective of this section is, therefore, to take a closer look at the issue of how to approach this limit value. One factor warranting particular attention is that even the calculation of the radiation dose for those who live closest to the final repository, as provided in the safety analysis, is marred by major uncertainties. For these calculations, an assessment must be made of the scope and speed of the radionuclides in making their way through the different barriers and to the surface of the earth. Additionally, an assessment must be made of the extent to which the different radionuclides that have made their way to the surface could be ingested by humans, via food or water. It is this overall uncertainty regarding all of these steps that requires careful consideration.

[157] ICRP. 1991. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60.
[158] The Swedish National Council for Nuclear Waste. 2016.

From doses to risk (or vice versa)

The risk criterion for a final repository for spent nuclear fuel

The 'harmful effects' referred to in the paragraph above are cancer and heritable adverse effects. Part of the assessment of the risk this stored nuclear fuel will pose to humans in the vicinity of the final repository is the issue of how great the risk of health effects (primarily cancer) is when exposed to ionising radiation. This topic is covered in depth in the Swedish National Council for Nuclear Waste's State-of-the-Art Report for 2016.[159] The current 'official' risk evaluation is that the likelihood of developing terminal cancer is 5.5% Sv^{-1}, which can also be expressed as follows: in a population exposed to 1 Sv, 5.5 extra cases of terminal cancer will occur per 100 individuals exposed. As the risk is assumed to have a linear relationship with the dose, this equates to 5.5 additional cases of cancer per 100,000 people at an exposure level of 1 mSv. This is the ICRP's most recent assessment, published in 2007, and like earlier assessments by the ICRP, it is based primarily on analyses of epidemiological studies of the approx. 100,000 people who survived the bombs dropped on Hiroshima and Nagasaki in 1945.[160]

Risks and health impacts of low doses

The lowest radiation dose with a significant effect in the form of an increased cancer risk has been observed in studies of the survivors of the bombs in Hiroshima and Nagasaki as being 100 mSv. However, reports have been published by authors who, following more thorough reviews, have reached a lower limit of approximately 20 mSv for observable effects of short-term radiation.[161] The estimated risks of lower doses are based on the fundamental assumption that the risk has a linear relationship with the dose. These observations concern short-term radiation, in the region of a few minutes. For chronic radiation the ICRP assesses the risk of developing cancer to be approx. 50% lower.[162]

[159] The Swedish National Council for Nuclear Waste. 2016.
[160] ICRP. 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37.
[161] Ozasa. 2012. "Studies of the mortality of atomic bomb survivors, report 14, 1950–2003: An overview of cancer and noncancer diseases."
[162] ICRP. 2007.

It is unrealistic to assume that in the future it will be possible to form a more certain assessment based on epidemiological material. Due to the low likelihood, a population of several million individuals would be required. The uncertainty in the assessed risk of health effects at low doses (<100 mSv) is, therefore, difficult to assess. For these kinds of low doses, the risk estimation is based on the hypothesis that it is possible to extrapolate data in a linear manner from the risks calculated for higher doses. It should also be noted that the risks stated are an average value for a large population – individual variations are considerable and dependent on a large number of factors, both heritable and environmental.

In the Council's 2016 State-of-the-Art Report, it was stated that the risk factor probably lies within a factor of five of the dose range 5–50 mSv.[163] If the risk were more than five times as large, it would have been observed in the epidemiological studies of the survivors of the atomic bombings, as well as in more recent studies of the thousands of nuclear power workers exposed to doses in the range 10–50 mSv. In addition to the risk of develop cancer, the risk of other forms of adverse genetic effects are included in the calculation. The figures used by SSM in its regulation SSMFS 2008:37 are the combined risk (cancer plus adverse genetic effects) for an average of the population, assessed in 1990 as being 7.3% Sv^{-1}.[164]

[163] The Swedish National Council for Nuclear Waste. 2016.
[164] 50 ICRP. 1991.

> Definitions
>
> *Absorbed dose*: Defined as absorbed energy per unit mass in J/kg, given using the special unit 'gray' (Gy).
>
> *Effective dose*: The absorbed dose from different kinds of radiation and to different organs in the body, weighted in a way that allows the risk to equate to a dose of gamma radiation evenly distributed in the body. Measured in sieverts (Sv). In theory, this concept allows all of the different risks in different exposure situations to be combined into one figure.
>
> *Committed dose:* A dose that will inevitably be received in the future. For example, if a radionuclide finds its way into the body, it will not emit any dose until it breaks down. If it is a long-lived substance, such as plutonium, this can take several years.
>
> *Dose constraint:* A limit value used in the planning of operations involving ionising radiation. This cannot usually be monitored using direct measurements.

Limit values and dose constraints

Up until 2017[165], SSM used the risk factors stated in ICRP 60[166] when setting limits for permitted doses in operations involving ionising radiation. Depending on the type of operations, and whether the party being exposed to radiation is employees or the public, the evaluation of what is an acceptable risk varies.

- Those who come into contact with ionising radiation in their professional role must stay below a maximum of 20 mSv/year. A criterion for this limit is that employment operations are assessed as safe when the risk of accidents with fatal consequences is less than 1 in 1,000 per year.

[165] A new law featuring minor changes is due in 2018. Based on ICRP. 2007.
[166] ICRP. 1991.

- The public may be exposed to a maximum of 1 mSv/year in addition to background radiation (which also includes radon). This limit is maintained by SSM setting requirements stating that a specific activity may not expose a single person to a dose exceeding 1/10 of this value. The additional risk of developing terminal cancer, of 0.005 % for 1 mSv, may be compared with the "natural" likelihood of dying of cancer, which is currently approximately 20% in Sweden.
- If the expected annual dose for a person (employee or public) amounts to up to 10 μSv per year (in addition to background levels), the activity can be regarded as an exception and does not need a license under EU Directive 2013/59.[167]

In terms of a final repository for spent nuclear fuel, the safety analysis's requirements on dose constraints are lower by a factor of 70 than the currently applicable dose for the public, which in turn is lower by a factor of 20–100 than the value at which health effects have been observable so far. Based on the risk of 1 per million, it can be calculated that a dose constraint of 0.014 mSv/year will be applicable to the final repository. It may be noted that both the international organisations that issue global recommendations regarding radiation safety, the ICRP[168] and the IAEA[169], state that the dose limit for a final repository should not exceed 0.3 mSv/year, i.e. 20 times higher than the dose decided upon by the SSM. (See table 3.1 below).

The reason for SSM opting to issue the dose constraint for the final repository at a level so much lower than the international recommendations has not been provided. One reason may be that the authority wishes to account for the uncertainties ingrained in the design of a final repository that is to guarantee safety for 100,000 years, as monitoring is not possible. Even in the instance of a relatively major misjudgement (a dose that is higher by a factor of 100) of the characteristics of the technical barriers or the rock, in

[167] Council Directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom. (Official Journal of the European Union L 13/1, 17 January 2014).
[168] ICRP. 2013. Radiological Protection in Geological Disposal of Long-lived Solid Radioactive Waste.
[169] IAEA. 2011. Disposal of radioactive waste.

practice this will not lead to observable consequences, even taking into account current uncertainties in terms of the risks of low-dose radiation.

Tabell 3.1 Comparison of dose limits and dose constraints for the public

	Dose	Remarks
Dose limit for the public	1 mSv/year	Background radiation and radon not included
Dose constraint for the public from a nuclear power plant, for example and Clink/Clab	0,1 mSv/year	The individual allowance per activity is a maximum of 1/10 of the dose limit
Dose constraints for the final repository	0,014 mSv/year	Derived from an accepted risk of 1 in 1 million
ICRP and IAEA, dose constraints for the public	0,3 mSv/year	Generally all activities, incl. final repository
IAEA – accidental intrusion into the final repository	1 mSv/year	*Disposal of radioactive waste.* (IAEA. 2011)
ICRP dose to which the public are exposed from a final repository	0,3 mSv/year	ICRP Publication 122. (ICRP. 2013)
Exemption level	0,01 mSv/year	License not required (Council Directive 2013/59/Euratom)

How have the international communities worked to reduce the uncertainties associated with the risks of ionising radiation?

Epidemiological studies of the approx. 100,000 people who survived the bombs dropped on Japan in August 1945 have long constituted the most important material for the assessment of the likelihood/risk of ionising radiation causing cancer. However, as the time delay from exposure to the effects becoming detectable can be long, so it is only now, just over 70 years later, that epidemiological research can reveal a full picture of the impact. Research over the last 20 years has contributed to a reduction in the uncertainties in the risk evaluation developed, thanks to:

- A more thorough statistical analysis, including a focus on ensuring that the control group is as representative as possible.
- Improved thoroughness in the dose evaluations.

- Improved models for age dependence, and how the risk varies with time from exposure.
- Epidemiological studies focused on specific organs.

In order to be able to reduce the uncertainties in risk evaluations, it is important that data from groups and populations who are exposed to radiation in other ways is produced and analysed. An expert group within the fields of epidemiology, dosimetry and radiobiology has recently reviewed a number of independent epidemiological studies of groups/populations exposed to low doses of ionising radiation, including those in the vicinity of the Chernobyl and Fukushima disasters, and people who worked in the nuclear weapons industry in the former Soviet Union.[170] Their conclusions are that a risk factor based on these new data corresponds well with the risk factor previously published as a result of studies focusing on the survivors of Hiroshima and Nagasaki.[171]This means that through active research into and monitoring of new groups who have been exposed to radiation in some way, it is possible to increase the reliability of the risk assessment by some degree. For example, when specific organs are exposed to radiation, there is a greater chance of seeing effects at lower doses, as the number of 'natural' instances of cancer is also lower.

Amongst the national and international organisations that study, assess and provide recommendations on radiation and its effects, the ICRP stands out as the one with the highest international standing and the greatest authority. With the possible exception of the USA, their recommendations form the basis for radiation safety regulations in almost all countries. Other organisations also work either to compile and analyse different sets of epidemiological data or to assess the risks that have emerged and provide recommendations. A summarised presentation of some of the key organisations can be found in the appendix below.

[170] McLean et al. 2017. "A restatement of the natural science evidence base concerning the health effects of low-level ionizing radiation."
[171] Ozasa et al. 2012.

Conclusions

- The uncertainty in the risk assessment that provides the basis for current limit values is significantly lower than it was a couple of decades ago, based on the fact there is more data available and a greater number of independent and more thorough analyses provided by international organisations.
- The 1990 Recommendations of the International Commission on Radiological Protection (ICRP 60)[172] includes presumptions and calculations that provide the basis for the limit value for the radiation dose that can be calculated based on SSMFS 2008:37. The ICRP's most recent risk evaluation gives a slightly lower risk with less uncertainty.[173]
- SSM's limit value for a future population group residing around the site of the final repository is 1/70 of the current limit value for exposure to ionising radiation from other radiation sources, and 1/7 of the dose constraint for the allowance for one radiation source.
- One reaction to greater uncertainties in dose evaluation is to institute a much lower limit value. This allows the margins created to 'take care of the uncertainty'.
- All in all, the dose constraints provided by SSM for the final repository, with good margins, can be considered safe.

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172 ICRP. 1991.
173 ICRP. 2007.

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SSM. 2008. SSMFS 2008:37 *The Swedish Radiation Safety Authority's Regulations Concerning the Protection of Human Health and the Environment in Connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste.* The Swedish Radiation Safety Authority.

Appendix information on international organisations

BEIR	Biological Effect of Ionizing Radiation	An organisation in the USA that carries out its own risk evaluations and assessments independently of the ICRP.
IAEA	International Atomic Energy Agency	a UN organisation based in Vienna International supervisory body. Works in parallel on policy issues and regulatory frameworks.
ICRP	International Commission on Radiological Protection	Established in 1928. Works on policy issues. Issues radiation safety recommendations.
RERF	Radiation Effects Research Foundation	A foundation that coordinates epidemiological studies of the survivors of Hiroshima and Nagasaki.
SSM	Strålsäkerhetsmyndigheten (The Swedish Radiation Safety Authority)	Licensing and supervisory authority etc. for radiation safety and nuclear safety in Sweden.
UNSCEAR	United Nations Scientific Committee on Effects of Atomic Radiation	UN-led international committee that compiles data from scientific literature.

ICRP

The ICRP was founded in connection at the second International Congress of Radiology in Stockholm in 1928. The reason for this was that it had long been known that x-ray radiation and the radiation from radium, which was used to treat cancer, could cause harmful effects in the staff providing the treatments. The harmful effects in question then were external effects, such as wounds and a loss of hair, but damage was also being caused to internal organs and blood cell counts. Initially, there were no adequate measuring methods and the rules only applied to the use of radiation within healthcare.

The ICRP consists of a Main Commission and four Committees. Under these Committees are working groups that carry out the actual work in terms of producing texts for publications in the Annals of the ICRP, which is released quarterly.

Over time, the ICRP has become a significant authority in terms of radiation safety recommendations. There are likely a number of intertwined reasons for this. One key factor is that they were the first to not just take note of the fact there were harmful effects, but to also take responsibility for researching how to avoid these effects, not to mention that this was taking place at a time when the public and media regarded radiation as healthy and providing those exposed with a magic glow.

UNSCEAR

UNSCEAR stands for the United Nations Scientific Committee on the Effects of Atomic Radiation, and was founded in 1956. In practice, it comprises a couple of representatives from each of the designated 25–30 countries. They compile and report on data and research results on the effects of ionising radiation, based on scientific literature. They also compile and report on observed levels of ionising radiation and radioactive substances in the environment, derived from different sources, as well as medical usage of ionising radiation.

BEIR

In the USA, the ICRP does not have as strong a position as it does in the rest of the world, even though citizens of the USA are members of both the Main Commission and the Committees. However, BEIR, which is a committee operating under the National Research Council, has also carried out risk evaluations and assessments, the results of which are in line with those published by the ICRP. BEIR VII also features age-dependent risk evaluations, from which it is evident that the risk for children can be up to four times that of the risk for adults.[174]

RERF

RERF is a Japanese-American research foundation established in 1975 in Japan in order for Japan and the USA to work together to pursue research into the medical effects of radiation, especially on the survivors of the 1945 atomic bombs. RERF continued the work on monitoring the health effects on survivors started by US-based

[174] NAS/NRC. 2006. Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2. Board on radiation effects research. National research council of the National Academies. Washington D.C.

researchers in 1947. On the basis of a more thorough analysis of the data, including better dosimetry and efforts to establish as representative a control group as possible, the aim is to produce significant results for even lower radiation doses. The results are published in scientific journals. Studies supported by foundation contribute to the basis of risk evaluations issued by the ICRP and BEIR.

IAEA

The IAEA is often colloquially termed the world's 'Atoms for Peace' organisation. Its task is to promote the development of nuclear power in poorer parts of the world, as well as the use of ionising radiation for other means. Furthermore, it forms part of a supranational supervisory authority. It also provides recommendations concerning radiation safety and radiation protection that are aimed specifically at states with less developed authorities for the purpose. However, the Basic Safety Standards released every few years are of particular interest to the radiation safety authorities in many countries.

4 Conclusion

Using its multidisciplinary approach, the Swedish National Council for Nuclear Waste has, on a number of occasions, looked at the different time perspectives of the nuclear waste issue in terms of a final repository for spent nuclear fuel in accordance with the KBS-3 method. The first perspective is the century-long establishment period, i.e. the time it will take to construct, operate and seal a final repository for spent nuclear fuel. The other is the 100,000 year perspective, which is the length of time for which the final repository must be able to serve as an effective means of protection against the dangerous fuel.

The century perspective

Provided SKB's final repository project goes ahead, establishing the facility will take the rest of the century. Other options may arise during this time, requiring flexibility and new ways of thinking.

A stepwise licensing process is, therefore, crucial in managing the challenges this long establishment period entails. The safety analysis reports compiled by SKB contain reference designs for different technical systems, with the intention that these designs will be supplemented with further detail as the project progresses. This increasing degree of detail is also important in terms of ensuring that analyses of the long-term safety become more reliable.

There are also challenges associated with a long establishment period as we do not know how society will change, meaning that having the capacity to adapt to both unexpected events in the project and changes in the surrounding world would be beneficial.

The 100,000 year perspective

In this State-of-the-Art Report, the Council has concentrated on two of the barriers in the KBS-3 method, i.e. the canister and the rock. They must be able to withstand the strain they may be placed under for at least 100,000 years.

In its 2011 application, along with supplements, SKB set out its arguments for these barriers being able to withstand the strains. In its pronouncement, the Land and Environment Court at Nacka District Court accepted SKB's assessment of the rock's protective capacity, but stated that there were a number of uncertainties remaining concerning the copper canister.

How should we tackle these uncertainties?

This State-of-the-Art Report deals with the concepts of uncertainty and risks. The uncertainties in question are different in nature, and some could be reduced during the stepwise licensing process. SKB's research must be transparent throughout the establishment period, both in the RD&D programmes and in SARs.[175]

The Land and Environment Court has drawn attention to uncertainties regarding the KBS-3 method. SSM assesses SKB as having the prerequisites to resolve the remaining uncertainties highlighted, and SKB emphasises that work on responding to these issues is underway. For this ongoing process, it is important that clarity is ensured on the time required to straighten out the remaining issues. The baseline scenario, which entails continued interim storage at Clab, is not a long-term solution. The issue of how long this storage can be used by is, nevertheless, key to the task of drawing up a realistic assessment of how long SKB has to modify and clarify the KBS-3 method, or whether other solutions are required. All of these matters entail financial and competence issues.

[175] More information is available in The Swedish National Council for Nuclear Waste. 2017. SOU 2017:62 Review of the Swedish Nuclear Fuel and Waste Management Co's (SKB's) RD&D Programme 2016.

Final remarks

The decision-making process is important in itself. In this respect, the experts' decision on the technology concerned is not sufficient by itself, and the Government will take a political decision, as a final repository will have a long-term impact on society. How can we approach the issue of decision-making in the face of uncertainty?

The nuclear waste issue is a complex one, in part because it can be divided up into different parts concerning different kinds of uncertainties. By being aware of the uncertainties that exist and the categories they fall into, it will, in all likelihood, be easier to find strategies to manage and monitor them. The best approach for unavoidable uncertainties is to be humble and aware of them, to be alert to the possibility of new uncertainties, and to ensure flexibility throughout the entirety of the project.

PART 2 The nuclear waste field

5 The work of the Swedish National Council for Nuclear Waste and the nuclear waste field

5.1 The work of the Swedish National Council for Nuclear Waste in 2017

During 2017 the Swedish National Council for Nuclear Waste (the Council) has worked in accordance with the Committee terms of reference 2009:31, and has monitored nuclear waste issues through means such as publications, meetings and seminars. Below is a short overview of the Council's work.

State-of-the-Art Reports 2017 and 2018

The Council's State-of-the-Art Report SOU 2017:8 *Nuclear waste – an ever-changing issue* was submitted to Minister for the Environment Karolina Skog on 24 February. Since then, the Council's work has included compiling the present State-of-the-Art Report, SOU 2018:8 *Nuclear Waste State-of-the-Art Report 2018. Decision-making in the face of uncertainty*.

Assess SKB's operations

In June, the Swedish National Council for Nuclear Waste submitted its review statement on SKB's 2016 (RD&D programme)[176] to the Ministry of the Environment and Energy On 1 December the Council met with Minister for the Environment Karolina Skog and State Secretary Per Ängquist, along with others, to present and discuss the Council's review in more depth. Representatives from SKB's management were also present at the meeting.

In the autumn, the Council attended the five-week main hearing at the Land and Environment Court at Nacka District Court as part of the licensing process for a final repository for spent nuclear fuel in accordance with the Swedish Environmental Code[177]. The Council did not take a stance on the application at the hearing as it does not constitute a part of the Council's role as advisor to the Government.

Meetings and seminars

The Council has held six Council meetings and a number of meetings with its target groups, including the municipality of Östhammar, SSM, SKB, the Ministry of the Environment and Energy, the Swedish National Audit Office and interested organisations.

The Swedish National Council for Nuclear Waste's State-of-the-Art Report SOU 2017:8 was presented at one of the Defence Committee's assemblies. The report was also presented to the Council's other target groups at an open seminar.

The Swedish National Council for Nuclear Waste organised two seminars during the so called Almedal Week in July, discussing long-term information preservation and future scenarios related to the nuclear waste issue.

In December, the Council assembled several of its target groups for a round-table conversation. Those represented included the Uppsala County Administrative Board, the Swedish NGO Office for Nuclear Waste Review (MKG), the Swedish Environmental

[176] The Swedish National Council for Nuclear Waste. 2017. SOU 2017:62 Review of the Swedish Nuclear Fuel and Waste Management Co's (SKB's) RD&D Programme 2016.
[177] Swedish Environmental Code (1998:808).

Movement's Nuclear Waste Secretariat (Milkas), Opinionsgruppen för säker slutförvaring (Oss / the opinion group for safe final storage), the municipality of Oskarshamn, the Regional Council of Kalmar County, the Swedish Renewable Energies Organization (SERO), SSM and the municipality of Östhammar.

International activities

The Council's role includes monitoring the development of nuclear waste and spent nuclear fuel management in other countries. In November, members of the Council undertook a study visit to Spain. The objective was to learn more about the decommissioning and dismantling of nuclear power plants and the management of low- and intermediate-level radioactive waste. In Spain, the state, through the organisation Enresa, is responsible for managing radioactive waste. The Council held meetings with Enresa and the supervisory authority CSN (Consejo de Seguridad Nuclear). The Council also visited the José Cabrera Nuclear Power Station, which is currently being decommissioned.

Additionally, the Council's members took part in a number of international conferences and working groups during the course of the year.

During autumn 2017, Hannu Hänninen, who serves as an expert at the Swedish National Council for Nuclear Waste, received the Henri Coriou Award in Prague at the European Corrosion Congress.

5.2 The nuclear waste field in Sweden in 2017

The licensing process for a final repository for spent nuclear fuel

The main hearing of the Land and Environment Court and its pronouncement for the Government

In March 2011 SKB submitted its applications for the final disposal of spent nuclear fuel to the Land and Environment Court and SSM. During the autumn 2017, the Land and Environment Court held its main hearing in accordance with the Swedish Environmental Code. The hearing at the Land and Environment Court concluded with a pronouncement submitted on 23 January to the Government, 2018 which will determine permissibility under the Swedish Environmental Code. The conclusions the Land and Environment Court reached included:

> SKB's investigation is thorough, however there are still uncertainties regarding the canister's capacity to contain the nuclear waste in the long term. These uncertainties relate to the extent to which the canisters can be damaged by corrosion and processes that impact upon their mechanical durability. The overall investigation shows that the uncertainties concerning the canister's protective capacity are significant, and that not all uncertainties have been considered in SKB's safety analysis.
>
> Based on the current safety analysis, the Court cannot reach the conclusion that the final repository will be safe in the long term. Therefore, the conclusion is that the final repository may be permitted under the Swedish Environmental Code only if SKB provides further supporting information that clarifies that the final repository is safe, covering in particular the canister's protective capacity.
>
> The final repository may be permitted with regard to the Swedish Environmental Code's requirements in terms of choice of location, special protection areas, and protected species. However, the operations entail a risk of substantial harm to the Forsmark-Kallriga bay area of natural interest, but the Land and Environment Court concluded that the national interest in final disposal should be given precedence. Permission is required for several Natura 2000 areas. If the safety measures are taken, permission may be granted for the Natura 2000 areas.
>
> Under the Swedish Environmental Code, those granted permission shall remain responsible for the operations until further notice, i.e. with no time limitations. There are different views on where long-term responsibility lies. The municipality of Östhammar has opposed the municipality taking ultimate responsibility. The issue arises as to whether the state should have ultimate responsibility for the final repository. It must be clarified who has the long-term responsibility under the Swedish Environmental Code.
>
> Prior to the granting of permission the Government ought to also consider certain legislative amendments, including assigning the

> Swedish Radiation Safety Authority a stronger position within the Swedish Environmental Code.[178] /translated from Swedish/.

The Land and Environment Court concludes that the Environmental Impact Assessment fulfils the requirements of the Swedish Environmental Code, and may therefore be approved. The Court also concludes that operations at Clab and Clink may be permitted under the Swedish Environmental Code.[179]

SSM's pronouncement for the Government

On the same day as the Land and Environment Court, SSM submitted its pronouncement under the Swedish Act on Nuclear Activities[180] to the Government. SSM writes that:

> The Swedish Radiation Safety Authority recommends that the Swedish Nuclear Fuel and Waste Management Company (SKB) is granted a license under the Swedish Act on Nuclear Activities to construct a final repository for spent nuclear fuel in Forsmark, in the municipality of Östhammar, and an encapsulation plant in the municipality of Oskarshamn.
>
> The Swedish Radiation Safety Authority is of the view that SKB fulfils the preconditions for the safe management and final disposal of spent nuclear fuel, ensuring that human health and the environment are protected from harmful radiation ...
>
> Based on its applications, The Swedish Radiation Safety Authority is of the view that SKB has shown that the facilities and relevant safety analysis reports can be developed in accordance with the establish procedure for stepwise licensing under the Swedish Act on Nuclear Activities. SKB is considered capable of developing the updated safety analysis reports for the construction, operation and long-term radiation safety, which will be reviewed and approved by the Swedish Radiation Safety Authority during future stages, if a license is granted by the Government.

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[178] http://www.nackatingsratt.domstol.se/Om-tingsratten/Nyheter-och-pressmeddelanden/Mark--och-miljodomstolen-lamnar-sitt-yttrande-till-regeringen-i-malet-om-ett-slutforvar-for-karnavfall/ (accessed 30 January 2018).

[179] Pronouncement summary of the Land and Environment Court. 23 January 2018. Case No M 1333-11 Document appendix 843. (See the whole pronouncement in Document appendix 842).

[180] Swedish Act on Nuclear Activities (1984:3).

> Our recommendation includes a number of conditions, including that the safety analysis reports and management systems for the facilities continue to undergo development in accordance with a stepwise licensing under the Swedish Act on Nuclear Activities. This means that at a number of different stages in an ongoing process, SKB must submit reports to be reviewed and approved by the Swedish Radiation Safety Authority before they may proceed with the next stage in the process ...
>
> A further condition for the recommendation is that during the design, construction and operation of the facilities, SKB continues to take into account significant issues in terms of radiation safety, bearing in mind the development needs identified by the Swedish Radiation Safety Authority in its review.
>
> The Swedish Radiation Safety Authority also proposes certain conditions for the Government's licencing of SKB's facilities. The conditions entail the facilities being built, owned and operated as stated in the applications, and that SKB is to develop safety analysis reports to be tested and approved by the Swedish Radiation Safety Authority prior to construction commencing, prior to the start of test operation, and prior to the facility being opened for routine operation.[181] /translated from Swedish/.

SSM and the Land and Environment Court have now submitted the applications to the Government, which is responsible for their further processing and making a decision on licensing/permissibility.

The licensing process for extension of the final repository for short-lived low- and intermediate-level waste (SFR)

At the end of 2014 SKB submitted applications for the construction of SFR to the Land and Environment Court and to SSM. SKB's original plans were for the repository to also be an intermediate storage facility for long-lived low- and intermediate-level waste whilst awaiting the opening of a final repository for long-lived radioactive waste (SFL). However, this changed in 2017 when SKB

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[181] https://www.stralsakerhetsmyndigheten.se/press/nyheter/2018/stralsakerhetsmyndighet en
-lamnar-yttrande-om-slutforvar/ (accessed 30 January 2018); SSM. 2018. Pronouncement on licensing for facilities for the final disposal of spent nuclear fuel. 23 January 2018. (A short version of the pronouncement is translated in English: SSM. Pronouncement on licence applications for permission to develop facilities for final management of spent nuclear fuel. Document no: SSM2011-1135-23).

decided not to carry out interim storage of long-lived waste in the planned SFR extension. SKB has also decided that the reactor tanks are to be segmented, which means that a third tunnel will not need to be built. The supplementary information phase of the application took place from 2014 to 2017, and the applications were announced by the Land and Environment Court and SSM on 11 December 2017.

RD&D Programme 2016 – SKB's research programme

SKB publishes its research programme every three years,[182] and the latest one was published on 30 September 2016.[183] During 2017 SSM circulated the programme for comments, after which it submitted its pronouncement to the Government. The Swedish National Council for Nuclear Waste submitted its independent assessment of SKB's research programme to the Government in June 2017.[184] Some of the Council's key points were that moving forward, SKB must ensure that the RD&D programme is more comprehensive and clearer, that the scope of the research programme is evident through a clear schedule and budget, and that SKB remedies the shortcomings in the RD&D Programme as described by the Swedish National Council for Nuclear Waste, concerning the technical barriers, primarily stress corrosion cracking, copper creep and so-called blue brittleness. The Government decision on the research programme is expected during spring 2018.

Plan 2016 – SKB's cost calculations

Every three years SKB submits a calculation of the costs for the Swedish nuclear waste programme to SSM, and the latest one was submitted at the beginning of January 2017. SSM proposed an increase in the fees, at an average of 1 öre per kilowatt hour (kWh)

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182 As per the Swedish Act on Nuclear Activities (1984:3).
183 SKB. 2016. RD&D Programme 2016. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste.
184 The Swedish National Council for Nuclear Waste. 2017. (SOU 2017:62).

for nuclear-generated electricity for the period 2018–2020. The Government approved the proposal.[185]

Amended Nuclear Safety Directive

The EU's amended Nuclear Safety Directive was implemented and became applicable in Sweden on 1 August 2017. The Swedish Act on Nuclear Activities, with the accompanying Ordinance[186], along with two SSM regulations (SSMFS 2008:1 and SSMFS 2014:2) have been amended to implement the Directive. The amendments include clarifications to the responsibility of licensees for the safety of nuclear technology facilities as well as requirements regarding safety objectives and for safety work to be continually assessed and verified.[187]

M 2017:05 Inquiry on the revision of the Swedish Act on Nuclear Activities

This inquiry covers increased coordination of the distribution of responsibilities under the Swedish Act on Nuclear Activities and the Swedish Environmental Code, reviewing the definition of nuclear waste and radioactive waste and how more suitable delimitations between Swedish and foreign waste can be formulated, as well as proposing regulations on ultimate responsibility after sealing of a final repository. A report on this assignment is to be presented by 1 October 2018. See Directive 2017:76[188] (in Swedish).

Amendments in legislation on financing

The regulations on the financing of nuclear waste management have been clarified. The legislative amendments came into force on

[185] http://www.regeringen.se/pressmeddelanden/2017/12/karnavfallsavgiften-hojs-fram-till-2020/ (accessed 30 January 2018).
[186] Swedish Ordinance (1984:14) on Nuclear Activities.
[187] https://www.stralsakerhetsmyndigheten.se/press/nyheter/2017/eus-andrade-karnsakerhetsdirektiv-genomfors-i-sverige/ (accessed 30 January 2018).
[188] http://www.regeringen.se/rattsdokument/kommittedirektiv/2017/06/dir.-201776/ (accessed 30 January 2018).

1 December 2017, stating, for example, that funds held in the Nuclear Waste Fund may be placed in shares, that it must be possible for funds not used as intended to be reclaimed by the Nuclear Waste Fund, and that it must be possible for those who have not spent the funds distributed appropriately to be liable to pay compensation for lost return on the funds.[189]

The Swedish National Audit Office has reviewed the nuclear waste management financing system

The Swedish National Audit Office's overall conclusion is that the review shows that there are significant uncertainties and disagreements regarding the extent of the future costs and revenue in the financing system. Furthermore, the financing system has likely been under-financed.[190]

SSM moves to Katrineholm

The Government has tasked SSM with relocating parts of its operations from Stockholm to Katrineholm, where the authority is to have its head office.[191]

The Swedish National Debt Office takes over duties

The Government has assigned the Swedish National Debt Office to take over SSM's duties under the Swedish Act and Ordinance on Financing of Management of Residual Products from Nuclear Activities. The transfer is set to take place on 1 December 2018.[192]

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[189] Report 2017/18:FöU2; http://www.riksdagen.se/sv/dokument-lagar/arende/betankande/reglerna-om-finansiering-av-karnavfallshanteringen_H501FöU2; http://www.regeringen.se/artiklar/2017/05/forslag-pa-forandringar-i-regelverket-for-karnavfallsfonden/ (accessed 30 January 2018).
[190] https://www.riksrevisionen.se/sv/rapporter/Rapporter/EFF/2017/Finansieringssystemet-for-karnavfallshantering/ (accessed 30 January 2018).
[191] http://www.regeringen.se/regeringsuppdrag/2017/08/uppdrag-till-stralsakerhetsmyndigheten-om-lokalisering-av-viss-verksamhet/ (accessed 30 January 2018).
[192] http://www.regeringen.se/regeringsuppdrag/2017/08/uppdrag-till-riksgaldskontoret-att-forbereda-och-genomfora-inordnandet-av-uppgifter-fran-stralsakerhetsmyndigheten/ (accessed 30 January 2018).

5.3 Government testing in accordance with the Swedish Environmental Code and the Swedish Act on Nuclear Activities

Parallel processes in accordance with the Swedish Environmental Code and the Swedish Act on Nuclear Activities.

SKB submitted its applications for licenses to construct, own and operate a final repository for spent nuclear fuel in March 2011. Permission under both the Swedish Environmental Code and the Swedish Act on Nuclear Activities is required for this.

The cases have been prepared by the Land and Environment Court at Nacka District Court and SSM, which on 23 January 2018 submitted their pronouncements to the Government, which is responsible for the continued processing and will make a decision on permissibility/licensing.

Permissibility – the provisions in the Swedish Environmental Code concern both the facility safety/radiation safety and other issues associated with a final repository facility, such as noise disruption, protection of natural and cultural environments, and preservation of diversity. The Government is also to review the application from a societal perspective, to determine whether the operations in question are permissible.

Licensing – the Swedish Act on Nuclear Activities is a more specialised piece of legislation with a restricted focus on radiation safety issues. The Government will consider licensing here.

The Government's permissibility assessment in accordance with the Swedish Environmental Code and licensing under the Swedish Act on Nuclear Activities

Preparation of the case

When the Land and Environment Court and SSM have submitted their pronouncements to the Government, and the documents have been registered, the Ministry's preparation of the case will commence. The permissibility assessment under the Swedish Environmental Code will be coordinated with the licensing assessment under the Swedish Act on Nuclear Activities. As the cases are comprehensive, the Ministry has appointed a group of officials from the Environmental Assessment Division, the Chemicals Division, and the Legal Secretariat.

Preparation of the case under the Swedish Environmental Code will, in addition to the normal preparation process, also include the submission of a formal question to the municipalities of Östhammar and Oskarshamn to determine whether they permit the construction of the facilities in question.

The preparation process will initiate the Government decision

The Government's decision on a Government case is the final outcome of a long and careful preparation process within the Swedish Government Offices. The preparation process may include supplements, for example. If the officials do not have sufficient information to reach a decision, further information may be sought. Some cases may be circulated for comment amongst authorities, institutions, municipalities, professional associations and others concerned.

When the examination of the case is completed, the officials will compile a proposal for a decision. The proposal will then be prepared with the other units concerned within the Ministry. In many instances, one case may also touch upon the areas of responsibility of several ministers, and must, therefore, be jointly prepared with their staff. All ministers must agree on the decision before it is raised at a cabinet meeting. Other ministries may have perspectives that differ from that of the Ministry of the Environment and Energy.

The Government makes joint decisions on all Government cases during the cabinet meetings that take place each week. This allows all ministers the opportunity to have a say on the decisions the Government makes. The Government is, together, responsible for all Government decisions.

The municipal vetoes – the municipalities of Oskarshamn and Östhammar

Under Chapter 17 Section 6 of the Swedish Environmental Code, the Government may only issue permission for a nuclear facility if the municipal council of the municipality in which the facility will be located has issued its approval. If the activity is of the utmost importance with regard to national interest, the Government may make an exception, or a so-called *Veto valve*.[193]

Permissibility and licensing

If the Government decides favourably regarding *permissibility* under the Swedish Environmental Code and *licensing* under the Swedish Act on Nuclear Activities, the case will be returned to the Land and Environment Court and SSM. The Land and Environment Court will then hold a second main hearing on topics such as conditions, after which it will decide to issue a license under the Swedish Environmental Code.

The Government delegates decisions on further conditions under the Swedish Act on Nuclear Activities to SSM. One condition will be the implementation of stepwise licensing.[194,195] (More information on stepwise licensing can be found in section 2.5).

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193 The Swedish National Council for Nuclear Waste. 2014. SOU 2014:11 Nuclear Waste State-of-the-Art Report 2014 – Research debate, alternatives and decision-making, see Chapter 7; The Swedish National Council for Nuclear Waste. 2013. SOU 2013:11 Nuclear Waste State-of-the-Art Report 2013 – Final repository application under review: supplementary information and alternative futures, see Chapter 2; The Swedish National Council for Nuclear Waste. 2011. Report 2011:2 Licensing under the Environmental Code and the Nuclear Activities Act of a final repository for spent nuclear fuel.
194 https://www.stralsakerhetsmyndigheten.se/omraden/radioaktivt-avfall/slutforvar/en-stegvis-provning/ (accessed 30 January 2018).
195 The Swedish National Council for Nuclear Waste. 2011.

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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 Swedish National Council for Nuclear Waste is an independent scientific committee whose members possess expertise in technology, science, ethics and the social sciences.

In February 2018 the Swedish National Council for Nuclear Waste published this State-of-the-Art Report in Swedish. This year's report (SOU 2018:8) is titled *Nuclear Waste State-of-the-Art Report 2018. Decision-making in the face of uncertainty.*

The analysis of the Swedish Nuclear Fuel and Waste Management Company's (SKB) applications for a system for the final disposal of spent nuclear fuel must adhere to a complicated process. Ultimately, it is the Government who will decide. The decision will be made based on a comprehensive provision of supporting scientific documentation, but given a final repository must enclose the dangerous fuel for hundreds of thousands of years, the circumstances surrounding the decision still entail a degree of uncertainty.

Based on its multidisciplinary approach, the Council highlights a number of issues from different perspectives. The introductory chapter covers key concepts such as uncertainty and risk, as well as ethical issues. After this, the topics covered include environmental impact assessments, competence management, information preservation, the state's ultimate responsibility, and stepwise licensing under the Swedish Act on Nuclear Activities. The next chapter focuses on technical issues regarding the barriers in particular, especially in terms of knowledge and uncertainties to do with the canister and rock.

The report can be downloaded at www.karnavfallsradet.se