Nuclear Waste State of the Art Report 2010

– challenges for the final repository programme

The Swedish National Council for Nuclear Waste Report

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To the minister and head of the Ministry of the Environment

The Swedish National Council for Nuclear Waste is an independent scientific committee whose mission is to advise the Government on nuclear waste and decommissioning of nuclear facilities.

In the month of February every year, the Swedish National Council for Nuclear Waste publishes an independent review of the current situation in the nuclear waste field, known as a state-of-the-art report. The purpose of the report is to shed light on issues which the Swedish National Council for Nuclear Waste considers particularly relevant and clarify the Council's viewpoints on these issues. The Swedish National Council for Nuclear Waste hereby submits this year's state-of-the-art report (the tenth in this series) entitled *Nuclear Waste, State-of-the-Art Report 2010 – challenges for the nuclear repository programme* (SOU 2010:6).

During 2009 the Swedish National Council for Nuclear Waste has held hearings and seminars to shed light on relevant issues and carried on discussions with actors in the Swedish final repository programme. At the same time the Council has followed other countries' final repository programmes. Based on the knowledge acquired in this way, the Council has identified two areas (challenges) as being of particular importance in this year's report. These challenges are the engineered barriers (the copper canister and the buffer) and retrievability.

The present report is endorsed by all members and experts in the Swedish National Council for Nuclear Waste.

English versions of the reports on the state-of-the-art in the nuclear waste field for 1998, 2001, 2004 and 2007 are also available.

Stockholm, January 2010

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1 Introduction

2009 has been an eventful year in the Swedish nuclear waste field.

In June 2009, the Swedish Nuclear Fuel and Waste Management Co (SKB) announced that they will apply for a permit to build and a licence to operate a final repository for spent nuclear fuel at Forsmark in Östhammar Municipality. A preliminary environmental impact statement became available in December 2009, and SKB plans to submit a licence application for a final repository for spent nuclear fuel to the Swedish Radiation Safety Authority and the environmental court at the turn of the year 2010/2011.

At the same time the safety of the engineered barriers in SKB's method for final disposal, the KBS-3 method, is being questioned. The durability of the copper canister in pure oxygen-free water has in particular been called into question by new research findings. But the properties of the bentonite clay have also been discussed during the year.

The issue of retrievability has received increasing attention internationally and is high on the agenda in many national nuclear waste management programmes. Various factors have contributed to this development: one is the climate issue, which has brought out the advantages of nuclear power as an energy source, while another is new reactor technology, where reuse of spent nuclear fuel is a possibility.

The Swedish National Council for Nuclear Waste therefore considers it important to shed light on these factors in this year's state-of-the-art report, and a brief summary of the Council's standpoints is provided here.

1.1 Challenging the engineered barriers

SKB's method for final disposal of spent nuclear fuel, the KBS-3 method, is based on a system of multiple barriers that are supposed to interact to meet the requirements on long-term safety. These barriers are *the copper canister*, *the buffer* (consisting of bentonite clay) and *the rock*. Besides the three barriers, another important component in the final repository is the backfill, which like the buffer consists mainly of bentonite clay.

Copper canister

During the past two years, a research team from KTH (the Royal Institute of Technology in Stockholm) has published research findings that cast doubt on the durability of the copper canisters and indicate a risk of corrosion in oxygen-free water. The Swedish National Council for Nuclear Waste is of the opinion that it is not possible at present to draw such far-reaching conclusions from their research results as Hultqvist and Szakalos do with regard to the long-term durability of copper canisters in the final repository, and that a series of investigations is needed to answer the questions that have arisen around this subject. The results of the KTH team may be correct, but uncertainties exist that must be cleared up.

The buffer

The buffer consists of natural bentonite clay, which can absorb water and swell to several times it original volume. The properties of the bentonite in both the dry and wet condition are crucial for how well the buffer in the bored deposition holes works, and it must be able to resist disintegration (erosion). This risk of erosion is currently being studied by SKB. However, the Council would like to call attention to the fact that the company must be much clearer in the requirement specification for the clay it gives to potential suppliers. Of particular importance are limits on impurities, the concentration of montmorillonite in the bentonite, and requirements on other minerals. The Council would also like to stress the importance of reporting clearly the research on which the requirements on bentonite content are based.

1.2 Retrievability

Retrievability and reversibility are two concepts that are currently being discussed in the national waste management programmes in many countries. They refer to the possibility of retrieving the nuclear waste from the final repository before, and possibly even after, repository closure. Requirements on and the implications of retrieval in the final repository programmes of different countries are presented in a recent study by the NEA (Nuclear Energy Agency). In some countries (for example France, Japan, Canada and the USA), retrievability is closely connected with the social acceptance of a final repository for spent nuclear fuel. The Council therefore believes that the issue must be put on the Swedish agenda – particularly since the attitudes of the Swedish people towards retrieval have become more positive over the past few decades.

2 Challenging the engineered barriers

2.1 Background

SKB's method for final disposal of spent nuclear fuel, the KBS-3 method, is based on a system of multiple barriers that are supposed to interact to meet the requirements on long-term safety. The method entails enclosing the fuel in a cast iron insert and encapsulating the insert in copper. The copper canisters are then embedded in bentonite clay at a depth of about 500 metres in the rock. In other words, the three barriers are the copper canister, the buffer and the rock (see Figure 1). Each of them has its special function to fill, and together they comprise a whole that is supposed to ensure a safe repository.

The copper canister plays a central role in the final repository for spent nuclear fuel. SKB describes it as the most important *isolating* component in the repository[1], i.e. it is the primary barrier intended to prevent the radionuclides in the fuel from getting out into the environment. It is thus of crucial importance for the repository.

The buffer consists of bentonite clay whose function is to prevent corrosive substances in the groundwater from reaching the canister, to protect the canister from minor movements in the rock and to retard any radionuclides that may escape from a leaky canister.

The rock is the third barrier. It is supposed to isolate the waste and give the canister and the buffer a stable chemical environment. Unlike the canister and the buffer, the rock is a natural barrier and will not be dealt with further here.

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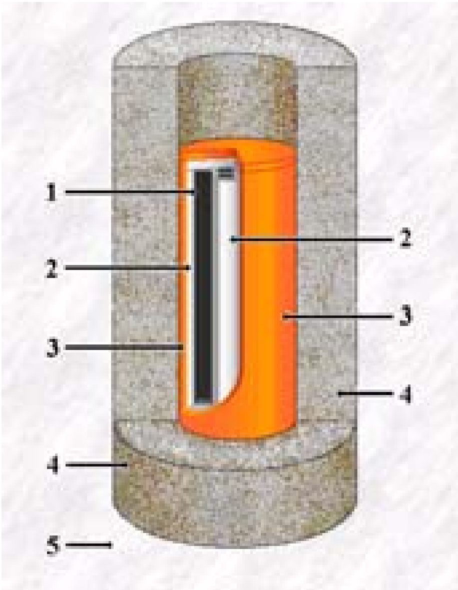
[1] See SKB R-07-24.

Besides the three barriers, the backfill is also an important component in the final repository. The backfill is the material with which SKB intends to backfill the tunnels when deposition of the canisters is finished, and like the buffer it consists mainly of bentonite clay. Since bentonite clay is the main component in both buffer and backfill, its properties are of very great importance for long-term safety. This subject is further discussed in section 2.3. But first (in section 2.2), the Swedish National Council for Nuclear Waste will present its view of the state-of-the-art in the canister field and the challenges faced by SKB.

Figure 1 Schematic illustration (not to scale) of the barrier system according to the KBS-3 concept



Description: Schematic illustration (not to scale) of the barrier system according to the KBS-3 concept. (1) Nuclear fuel consisting of pellets of uranium dioxide enclosed in Zircaloy tubes. Both the spent nuclear fuel and the Zircaloy tubes are poorly soluble, which hinders the leaching of radioactive isotopes in contact with water. (2) Insert of steel, which acts as radiation protection and provides mechanical stability. It delays water penetration if the copper canister has been damaged. (3) Copper canister, which is extremely corrosion-resistant under the chemical conditions prevailing in the repository. (4) Bentonite buffer, which is supposed to restrict the flow of groundwater to the canister and prevent the escape of radionuclides into the surrounding environment. (5) Surrounding rock. If radionuclides should get through the buffer, further transport in groundwater through rock fissures is impeded by precipitation and sorption on rock surfaces and mineral particles. In other words, the surrounding rock is supposed to help prevent radionuclides from reaching the biosphere.

2.2 Challenging the properties of the copper canister

2.2.1 The properties of the copper

Copper is a relatively rare element, constituting only about 0.007 percent of the mass of the Earth's crust. Together with silver and gold it forms the "copper group" among the elements in the periodic system, also known as the "coin metals".

Copper is a sought-after material in many structures due to its mechanical properties, its electrical conductivity, its attractive appearance and its relative immunity to corrosion. SKB writes in its report *Barriärerna*[2] ("The Barriers") that

> ...copper has been chosen as the material for the outer shell because it is very resistant to corrosion in the oxygen-free conditions that prevail in a deep repository. If there is dissolved oxygen in the groundwater, however, the copper shell corrodes.

It is above all properties such as corrosion resistance and mechanical stability that have made copper a natural choice as a barrier in the repository, and since the canister must fill its function for more than 100,000 years, there must be no questions concerning its properties. Conditions in the repository will change with time and the canister must be able to cope with all expected conditions, and some provision must also be made for unexpected events. The copper canister is the industrial product that is expected to have by far the longest function time, and the requirements must be formulated accordingly.

2.2.2 What does copper corrosion entail?

Corrosion is the result of a reaction, chemical or electrochemical, between a material and its surrounding environment. We usually associate corrosion with the rusting of iron, but malachite/verdigris on copper or white rust on zinc are examples of other corrosion products.

Corrosion leads to a weakening of the material, and in the final repository this could lead to leakage of radionuclides out into the groundwater and further to the biosphere.

A distinction is made between corrosion in the presence/absence of oxygen. Copper always corrodes in the presence of

[2] February 2002.

oxygen. However, it has previously been assumed that copper cannot corrode in oxygen-free environments, unless these environments contain sulphide or chloride ions. SKB has therefore adopted measures to minimize the presence of sulphide ions in the surroundings of the copper canister, for example by imposing special requirements on the composition of the bentonite clay. SSM and the Swedish National Council for Nuclear Waste have so far focused on corrosion in the presence of sulphide and chloride ions.

Recently, however, Dr Peter Szakálos and Professor Gunnar Hultqvist from KTH (the Royal Institute of Technology in Stockholm) published results that cast doubt on this assumption.[3] They say that their research, which is based on results which Hultqvist presented more than 20 years ago, shows that copper can actually corrode relatively extensively in pure oxygen-free water.[4] Their results have in turn been questioned by SKB, which says that the new research results are not convincing, and are to some extent contradictory. SSM and their expert panel in the area have also questioned the results.

Infobox 1: The presence of oxygen after deposition

The time after deposition of the copper canisters in the final repository is divided into an aerobic and an anaerobic period, according to the availability of oxygen in the form of gas or dissolved in the water. During the aerobic period immediately after deposition there is a relatively good supply of oxygen in air pockets in the bentonite and dissolved in the groundwater, and it can be assumed that the surface of the copper canister will be covered with some corrosion product.

As the oxygen in the repository is consumed by reactions with impurities in the bentonite clay, the repository gradually becomes anaerobic, i.e. oxygen-free. This anaerobic state is expected to last for a very long time, which means it is vital to predict what will happen then. The big threats to the copper canister during this period have been considered to be the hydrogen sulphide ions and chloride ions that may be present in the groundwater.

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[3] *Corrosion of Copper by Water in Electrochemical and Solid-State Letters 2007 and Water Corrodes Copper* in Catal. Lett. 2009.

[4] G. Hultqvist, *Corrosion Science*, 1986, “Hydrogen Evolution in Corrosion of Copper in Pure Water”.

The Swedish National Council for Nuclear Waste adopts an open-minded but sceptical attitude to the research team's results, particularly with respect to the far-reaching conclusions drawn by the researchers regarding the durability of the copper canisters in the final repository. We will therefore focus on these new research findings in the rest of this publication.

2.2.3 Does copper corrode in oxygen-free water? A scientific controversy

Szakálos and Hultqvist assert that their experimental results suggest that copper can be oxidized by hydrogen ions in pure water under oxygen-free conditions, even in the absence of other ions. The hydrogen ions are reduced by the process and form hydrogen atoms, plus an as-yet unidentified corrosion product. The hydrogen atoms can either combine to form hydrogen gas or be absorbed and dissolved by the metallic copper.

Szakálos and Hultqvist say that if the hydrogen gas disappears from the system, the process can continue as long as water remains. They further claim that copper can become embrittled when the hydrogen gas penetrates into and is dissolved in the metal. The researchers' results indicate that the corrosion rate for copper in water is several orders of magnitude greater than has been indicated by SKB, which is a challenge to the function of the copper canister in the final repository. The researchers themselves predict that the copper canisters in the repository could corrode in a few hundred years, and even before then they will have been weakened mechanically by the hydrogen generated in the process and absorbed by the metal.

Part of Hultqvist's and Szakálos's argumentation is based on observations of the copper coins from the royal warship Vasa, which was relocated in 1961 after having lain in the mud on the seafloor outside Stockholm since 1628. Hultqvist and Szakálos assert that the conditions there greatly resemble the anaerobic conditions which the copper canister will encounter in the repository.[5] The copper coins from the Vasa are severely corroded, which the research team has taken as an indication that the canister will also corrode in a relatively short time. This opinion has been criticized by SKB, which points out the high concentrations of impurities in the bottom sediments. These particularly include

[5] "Water Corrodes Copper" (Catal. Lett. 2009).

sulphide ions, which have well known corrosive properties for copper, even under oxygen-free conditions.

In order to clarify where the scientific community stands in this question, the Swedish National Council for Nuclear Waste arranged an international scientific workshop on "Mechanisms of Copper Corrosion in Aqueous Environments" in Stockholm on 16 November 2009. The purpose was to discuss the fundamental mechanisms of copper corrosion in oxygen-free water and to identify what further information is needed to determine whether this corrosion mechanism really occurs and to assess its importance for the long-term safety of a final repository of the KBS-3 type.

The conclusions of this workshop are that the KTH team's results may be correct, but that uncertainties exist that must be cleared up. A series of investigations is required to answer the questions that have arisen on this topic. The invited experts[6] are, however, agreed that the experimental results showing that copper is oxidized spontaneously in oxygen-free water by the reduction of protons (hydrogen ions) is not supported by published thermodynamic data (second law of thermodynamics) and conflicts with accepted knowledge and experience. Most experts also question the interpretation of the experimental results made by the research team from KTH and say that the proposed corrosion product must be characterized better and it must be determined whether it constitutes a separate (three-dimensional) phase or is a result of reactions on the copper surface on a limited scale. But SKB's reports and conclusions concerning copper corrosion should also be subjected to more extensive critical review. For example, one of the experts believes that an extensive analysis should be performed to determine what conditions must be met to minimize corrosion of copper in the repository. The system should be modelled as a function of the parameters that are expected to vary with time, for example temperature, pH, sulphide ion concentration and hydrogen gas pressure.

Key questions in this context are the stability and other properties of the resulting corrosion product. Does it constitute a separate stable phase or does it consist of a thin film adsorbed on the metal surface? This distinction is important since it determines whether the corrosion reaction is a "bulk reaction" where the metal is subject to deep and long-lasting attack, or whether it is a surface reaction whose rate can be expected to decrease with time, pro-

[6] Dr Gaik-Khuan Chuah, Dr Ron Latanision, Prof. Digby Macdonald and Dr David Shoesmith.

vided water cannot flow freely to the metal. The discussion is thus not primarily concerned with whether copper can react with water, but rather what the scope of this reaction is; i.e. whether it seriously affects the bulk metal or is limited to the surfaces.

A complete account of the presentations made by invited scientists from KTH and SKB and the expert panel and their final conclusions will be presented in a special report in the spring of 2010.

Infobox 2: Various corrosion mechanisms

Corrosion of copper always entails that metallic copper, Cu^0, is oxidized to ionic form, Cu^+ Cu^{2+}, which can occur if copper donates electrons to a receptor in the surrounding environment such as oxygen molecules (O_2), which then form oxide ions, (O^{2-}), or hydrogen ions, H^+, which then form gaseous hydrogen, H_2. The chemical mechanism that is proposed by the research team from KTH can be described in simplified terms by the reaction formula:

$$Cu^0 + H_2O \Leftrightarrow CuOH? + \tfrac{1}{2} H_2 (g) \quad (1)$$

Cu^0 stands for metallic copper and the question mark after CuOH (= copper[I]hydroxide) in the formula means that the composition of the reaction product is unknown.

A key question in this context concerns the stability and other properties of the resulting corrosion product CuOH. Does it constitute a separate three-dimensional phase or does it consist of a thin film adsorbed on the surface and should therefore be written ≡CuOH (≡ designates the metal surface)?

The distinction is important since it determines whether the corrosion reaction is a "bulk reaction" or a surface reaction (2). In the latter case the reaction can be written:

$$\equiv Cu + H_2O \Leftrightarrow \equiv CuOH + \tfrac{1}{2} H_2 (g) \quad (2)$$

This reaction is supported by previous research (e.g. E. Protopopoff and P. Marcus; Electrochimica Acta, 51, 408 [2005]) and also results in hydrogen gas evolution, as previously shown by G. Hultqvist et al. in their experiments.

The discussion is thus not primarily concerned with whether copper can react with water by hydrogen gas evolution, but rather under what conditions and to what extent this reaction takes place, i.e. whether it is limited to the surfaces or seriously affects the bulk metal.

Known thermodynamic relationships indicate that both reaction (1) above and reaction (3) below are improbable in water, while reaction (4) is probable in both air and oxygen-containing water and can therefore be expected to occur on the copper canister during the initial period in the repository:

$$2Cu^0 + H_2O \Leftrightarrow Cu_2O + \frac{1}{2} H_2 (g) \quad (3)$$

$$2Cu^0 + \frac{1}{2} O_2 \Leftrightarrow Cu_2O \quad (4)$$

Reaction (4) thus entails that the copper canister will always have a layer of copper oxide on the surface under aerobic (oxygen-rich) conditions.

This layer can also contain chloride (Cl^-), carbonate (CO_3^{2-}) or sulphate (SO_4^{2-}) if the ions are present in the surrounding environment.

Copper can corrode under oxygen-free (anaerobic) conditions by e.g. reaction (5) below:

$$2Cu^0 + H^+ + HS^- \Leftrightarrow Cu_2S + H_2 (g) \quad (5)$$

Or by an equivalent reaction where the Cu^+ ions form compounds with chloride (e.g. $Cu_2(OH)_3Cl$).

It is these reactions which SKB assumes represent the greatest long-term threat to the copper canister in the final repository, and measures have therefore been adopted (e.g. requirements on the composition of the bentonite) to minimize the presence of sulphide ions in the bentonite clay.

2.2.4 Conclusions of the Swedish National Council for Nuclear Waste

Different possibilities for corrosion of the copper canister in the final repository were described in the Swedish National Council for Nuclear Waste's Review of SKB's RD&D Programme 2007 (SOU 2008:70). The Council's conclusions concerning corrosion were summarized in the following challenges to SKB:

- Continued corrosion studies are required in different areas: accelerated long-term stress corrosion cracking experiments, general corrosion in chloride- and sulphide-containing water with bentonite, and microbial corrosion.

- Mechanisms of copper corrosion in oxygen-free water must be investigated experimentally to determine whether corrosion of copper by hydrogen evolution can take place in pure, deionized, oxygen-free water and in groundwater with bentonite.

Against the background of recent discussions, the Council finds good reason to continue to abide by these conclusions.

SKB believes that the question of mechanisms of copper corrosion in pure water under anaerobic conditions is primarily a question for the scientific community. They believe that SKB's part is to show that the KBS-3 method with its multiple barrier system is sufficiently robust to cope with corrosion of the copper canister of the scope described by the research team from KTH. However, the Council believes that SKB must demonstrate in what way the safety assessment can be used to prove this contention.

The discussion of copper corrosion mainly concerns everything that happens to the copper canister under anaerobic conditions and low concentrations of sulphide and chloride ions in the bentonite's pore water that is in contact with the canister. When conditions change from aerobic to anaerobic, the surface of the copper canister will be covered with an extensive layer of corrosion products formed during production and transport of the canisters. The canisters will furthermore have a relatively high temperature ($\approx 100^{\circ}$ C) and reactions with oxygen can be expected to continue for a relatively long time in the deposition hole.

There is at present no reliable estimate of how long copper corrodes by oxidation with oxygen in the surrounding environment, i.e. how long the canister will be present in an aerobic environment. The Council believes that SKB should find out more about this period in terms of its length and the mechanisms that describe the processes that occur on the canister when conditions change from aerobic to anaerobic. What long-term consequences do these processes have for the copper canister?

Even if SKB believes that the recent discussion of copper corrosion in oxygen-free water does not have any decisive influence on the long-term safety of the repository, it has created uncertainty concerning the copper canister as a credible long-term barrier. The Council finds that SKB should actively work to ensure that the question of corrosion of copper in pure oxygen-free water is investigated in a scientifically correct manner to determine whether it is important or not.

The Council is of the opinion that it is not possible at present to draw such far-reaching conclusions from their research results as Hultqvist and Szakalos do with regard to the long-term durability of copper canisters in the final repository. Hultqvist and Szakálos have studied corrosion of copper coupons in beakers filled with water in a laboratory environment, and there is a great difference between these and 5 cm thick copper canisters surrounded by bentonite in the final repository. Furthermore, a possible explanation of Hultqvist's and Szakálos's observations is that the reaction observed is not a bulk reaction but a surface reaction. But further investigations are needed to determine this.

On the other hand, the recent discussion as to whether copper corrodes in pure oxygen-free water has made it clear that specific knowledge is lacking of what happens on the surfaces of the copper canisters when conditions change from aerobic to anaerobic. The Council concludes this in view of the research results presented by the research team from KTH, but also the results on corrosion of heated copper tubes in bentonite presented by SKB. One question that needs to be answered is how the continued process is affected by the quantity and composition of the oxidation products already present on the surfaces when conditions become oxygen-free.

In the opinion of the Council, not enough studies have been done of copper corrosion under the conditions expected in the repository. In SKB's report[7] studies of copper corrosion were not the primary purpose; instead, the focus was on how the bentonite was affected in the repository. Because so few studies have been done of how copper behaves in the repository environment, the results of this study have been interpreted and in some cases over-interpreted with respect to corrosion of copper in contact with bentonite. The Council therefore believes a study is called for with a focus on corrosion of copper in the environment expected to exist in the repository, i.e. under both aerobic and anaerobic conditions. The results of the projects presented to date are ambiguous and allow far too much room for interpretations that can be used to support completely different hypotheses with respect to the long-term properties of the copper canister in the repository environment.

Corrosion processes in oxygen-free (anaerobic) environments often produce hydrogen as a by-product (of water) and it is known that hydrogen can be dissolved by metals and greatly reduce

[7] Rapport TR-09-29, *Long term test of buffer material at the Äspö Hard Rock Laboratory, LOT project*.

mechanical strength due to hydrogen embrittlement. Copper has been shown to have a relatively low solubility for hydrogen, but even a small reduction of mechanical strength could affect its function in the long term. The Council therefore believes it is important to eliminate any doubt about hydrogen embrittlement of copper, particularly in view of the ductility of the canister when subjected to high compressive stresses.

Another consequence of high pressures when the bentonite is water-saturated and swells and during a glaciation is stress corrosion cracking. This can be particularly serious in the repository, since water supply and water saturation of the bentonite are so uneven. The canister can then be subjected to large flexural stresses, which increases the risk of stress corrosion cracking. A risk area for local corrosion is the area around the welded joints on the canister. This is particularly true when chloride ions are present in the groundwater.

The Council therefore urges SKB to carry out and present the results of further research on hydrogen embrittlement test and stress corrosion cracking.

2.3 Challenging the properties of the bentonite

2.3.1 The properties of the bentonite

The buffer is the second barrier in the multiple barrier system and is supposed to surround the copper canister in the final repository. It has a number of important functions for the long-term safety of the repository and consists of a natural clay that can absorb water and swell to several times its original volume.

This clay, bentonite clay, has been formed by sedimentation and transformation of volcanic ash and consists largely of the clay mineral montmorillonite. Bentonite is usually found as clay strata in sedimentary rock types. Different types of bentonite are sodium bentonite, calcium bentonite and sodium-activated bentonite, which is formed by adding chemicals to the calcium bentonite in order to make it more like sodium bentonite.

The properties of the bentonite in both the dry and wet condition are crucial for how well the buffer works in the bored deposition holes. The bentonite clay is also an important constituent of the backfill in deposition tunnels and other voids in the rock created during the construction of the repository.

Bentonite in the buffer takes the form of compact rings that are slipped over the copper canister in the deposition hole, while the backfill consists of compacted blocks or pellets that are deposited in the transport tunnels. Recently, the long-term properties of both the buffer and the backfill have been challenged by new and old research findings regarding the scope and importance of bentonite erosion.

One of the most important properties of bentonite is that it expands a great deal when it absorbs water – and sodium bentonite does this better than calcium bentonite. On the other hand, the clay must resist disintegration under certain conditions – and then calcium bentonite can work better.

2.3.2 Swelling and erosion of the bentonite

Inflow of water to the deposition holes is mainly expected to take place through fractures in the surrounding rock. If the inflow is greater locally than the bentonite is able to absorb, water will accumulate in the deposition hole and exert pressure on the buffer. The reason water can accumulate in this manner is that the swelling bentonite has an initial consistency that may be too soft to stop the inflow of water, and besides pressure on the buffer, another consequence of this accumulation of water can be erosion of the bentonite. Erosion in this context entails a disintegration of the bentonite to small particles, which can be carried away by the flowing water.

The causes of erosion of bentonite buffers have been studied and understood for a relatively long time. But what is challenging is to ensure that this erosion does not occur on a scale that threatens the long-term properties of the bentonite. Of particular importance in this context is the bentonite clay's natural content of monovalent and divalent ions.

Bentonite has a natural content of positive ions which are responsible for the ability of the clay to absorb water and swell. Sodium bentonite contains monovalent sodium ions, while calcium bentonite contains divalent calcium ions. SKB describes that the swelling capacity of the bentonite is largely determined by the clay's content of monovalent or divalent ions and by the surface charge on the particles.[8] Monovalent ions favour swelling while divalent ions and high surface charge adversely affect swelling

[8] In TR-09-06.

capacity, and there may be some negative correlation between the swelling rate of bentonite in water and its ability to resist erosion.

Rapid and extensive swelling is desirable if water saturation and swelling can take place in a space where the volume of the bentonite is limited so that a high density can be obtained in the end. Here monovalent ions are preferable. As far as the ability to resist erosion in the long term is concerned, however, it can be an advantage if the particles are held together by divalent ions, which bind more strongly to the surfaces of the clay particles and are not as readily washed away by flowing water.

This is how it works:

Positive ions neutralize the negative charge on the surfaces of the clay particles, causing the smallest constituents of the bentonite, tiny colloidal particles, to be attracted to each other and form larger aggregates. These aggregates are held together by the bonding capacity of the surrounding water (hydrogen bonds). Here, monovalent sodium bentonite would thus be preferable.

An important cause of erosion is, however, that the positive ions, which were previously bonded to the surfaces and created attraction between the particles, can be washed away by flowing water. As a result, the particles take on the same negative charge and instead repel each other, so that the large aggregates can disintegrate again to small particles that are carried away by the water (erosion). Here, divalent calcium bentonite would thus be preferable.

In the early post-closure period in the final repository, it is advantageous if the bentonite swells rapidly. But after a glaciation, with the large quantities of meltwater that are created when the ice melts, the requirement on a clay with stronger ionic bonds is central in order to reduce the risk of disintegration and erosion. These conflicting requirements on resistance to corrosion must be particularly taken into account by SKB.

2.3.3 Processes at the interfaces

The risk of extensive erosion is probably greatest when the bentonite has been allowed to swell without sufficient counterpressure, since this causes it to assume a gel-like and loose consistency where the particles are readily disintegrated and carried away by the water. This is less of a problem in the deposition holes, where the counterpressure from the surrounding rock is normally great, but more of a problem at the interfaces between the backfill and the rock.

SKB intends to backfill the tunnels with blocks of compacted bentonite clay and create a seal against the surrounding rock using bentonite pellets. However, the large quantity of pellets needed to seal the spaces between blocks and rock entail that the method is very sensitive to piping and erosion.

Another interface in the repository of specific interest is the interface between the copper canister and the surrounding bentonite. The recently published report from the LOT project[9] showed that corrosion products from a heated copper tube have been transported several centimetres into the surrounding bentonite. Whether it is assumed that this transport of copper derives from corrosion products formed under aerobic or anaerobic conditions, it is obvious that the bentonite affects the corrosion process by transporting the reaction products away from the surface of the copper canister.

A major study of the impact of bentonite on corrosion of copper is therefore needed, with an emphasis on both aerobic and anaerobic conditions. It would then be of special interest to study the exact copper material that will be used in the copper canisters at elevated temperature as well.

2.3.4 The composition of the bentonite

When it comes to the requirements on the composition of the bentonite, aside from a high concentration of montmorillonite, it may very well be a question of finding compromises where different properties are balanced against each other. Examples are resistance to erosion or the best possible swelling capacity, as well as different contents of impurities that can have a positive or negative effect on the properties of the bentonite under certain conditions.

Common impurities in the bentonite include both organic substances such as hydrocarbon compounds and inorganic substances such as calcite, gypsum and pyrite. Organic compounds and pyrite consume oxygen that is present in the bentonite from the start and that is carried away with the groundwater when the bentonite swells. Organic substances ultimately produce mainly carbon dioxide and water as end products, while the pyrite reacts to form sulphate ions, at the same time as hydrogen ions (H^+) are liberated

[9] SKB Technical Report TR-09-29.

and the water becomes more acidic, which means a lower pH. Consumption of oxygen in the bentonite is mainly positive, assuming that the copper canister does not corrode in oxygen-free water, whereas sulphate ions (like sulphide ions) pose a long-term threat to the canister. Sulphate ions can be reduced to sulphide ions by bacteria in the bentonite, and the sulphide ions cause corrosion of copper in an anaerobic environment. SKB's requirement specification therefore includes restrictions on the concentration of sulphide ions, the total sulphur concentration[10] and the total concentration of organic substances.

2.3.5 Conclusions of the Swedish National Council for Nuclear Waste

Nearly all of SKB's research and demonstration projects have been based on a given bentonite clay (MX-80), which has specific properties. This specific bentonite has been studied over a long time with respect to a large number of properties considered to be important for the buffer.

Recently, however, SKB has arrived at the conclusion that this clay can be replaced with a wide variety of bentonites of different grades, as long as they meet certain basic requirements. Besides limit values of the impurities mentioned above, SKB intends to only require a minimum value of 75 percent for the concentration of montmorillonite in the bentonite. Montmorillonite is the main clay mineral that lends the bentonite the property of swelling in water and normally comprises 75–90 percent of the total composition. Other important minerals in natural bentonite are quartz and feldspar as well as calcite, gypsum and pyrite.[11] These minerals also affect the properties of the bentonite in different ways and should be specified more clearly in SKB's requirements.

One reason for the relatively general requirement specification is that SKB can then be open to a large number of suppliers, reducing its dependence on a single supplier. However, the Council finds that SKB has formulated far too general requirements on the composition of the bentonite to be used, and that SKB must present the research and testing that has led to this judgement.

SKB is currently conducting intensive development work in its new Bentonite Laboratory on the function of the bentonite in

[10] Sulphide ions + sulphate ions.
[11] For a more detailed description, see the Council's previous review SOU 2008:70.

buffer and backfill. This work is above all concerned with questions related to swelling and erosion, particularly in connection with backfilling of deposition tunnels and voids. The problems associated with buffer erosion will be further studied. This applies in particular to the interfaces between buffer and backfill and between backfill and rock. It has also turned out that there are more technical challenges than expected in conjunction with the backfilling of tunnels and voids in the rock surrounding the final repository.

The Swedish National Council for Nuclear Waste is of the opinion that the composition of the bentonite and its content of impurities should be studied in conjunction with copper corrosion under aerobic and anaerobic conditions at elevated temperature. What does it mean that the bentonite in the form of rings, blocks or pellets remains unsaturated for a very long time? How does this affect the desirable properties ascribed to a fully water-saturated bentonite? These are some of the questions to which the Council eagerly awaits answers.

The Swedish National Council for Nuclear Waste is following SKB's work with great interest and looks forward to a more definitive decision on choice of materials and method. The Council would also like to stress the importance of reporting more clearly the research on which the requirements on bentonite content are based.

3 On retrievability

Abbreviations

ANDRA	Agence nationale pour la gestion des déchets radioactifs, established 1991
CoRWM	Committee on Radioactive Waste Management
IAEA	International Atomic Energy Agency
KASAM	Former Swedish name of the Swedish National Council for Nuclear Waste
NEA	Nuclear Energy Agency
NWMO	Nuclear Waste Management Organization
OECD	Organization for Economic Cooperation and Development
SKB	Swedish Nuclear Fuel and Waste Management Co
SKI	Swedish Nuclear Power Inspectorate, now SSM
SOM Institute	Society Opinion Media
SSI	Swedish Radiation Protection Authority, now SSM
SSM	Swedish Radiation Safety Authority, formerly SKI and SSI
STUK	Säteilyturvakeskus (Finnish Radiation and Nuclear Safety Authority)

3.1 Retrievability reconsidered

Should the final repository be designed to permit retrieval of nuclear waste that has already been deposited? This question has come up now and again in the nuclear waste debate since the late 1980s, and now it is on the agenda once again. Various factors have contributed to this development. The climate issue has brought out the advantages of nuclear power as an energy source, and new reactor technology offers potential for reusing spent nuclear fuel. The Swedish people have become more positive to retrieval, and the issue has also been given a prominent position on the international agenda.

In this state-of-the-art report, the Swedish National Council for Nuclear Waste would like to:

- examine the different sides of the issue and some fundamental principles,
- briefly sum up the international discussion, SKB's attitude and certain technical matters, and
- summarize the arguments and clarify the Council's position in the matter.

We hope this publication will serve as a basis for a further dialogue on the final repository issue, and in particular on the question of whether provisions should be made to retrieve spent nuclear fuel from a final repository.

3.1.1 Retrieval, retrievability, reversibility and stepwise decision-making

Retrieval entails bringing up one or more nuclear waste canisters from the repository to the ground surface to be either reused or disposed of in another manner.

Retrievability is a characteristic of the final repository and denotes the technical feasibility of retrieval. Such retrieval is technically simplest before the buffer has been placed around the canister in the deposition hole, more difficult after the deposition tunnels have been filled and sealed, and most difficult – as well as most costly – after the whole repository has been closed (see Figure 3).

Reversibility[1] is a broader concept than retrievability and denotes the possibility of reversing one or a series of steps in repository planning or development at any stage in the process. This implies the review and, if necessary, re-evaluation of earlier decisions.

Applied to the nuclear waste project, it entails the possibility of reviewing such aspects as new technology or social acceptance at

[1] In Swedish *omvändbarhet*.

different steps in the process (for example after emplacement of the copper canisters in the deposition hole, after embedding of the copper canisters, after backfilling of the deposition tunnels or even after closure of the whole repository). Based on this review, a decision can be made to either proceed or go back one or more steps. In Sweden, SSM's regulations assume that monitoring and maintenance of the final repository will continue until final closure of the repository, which means that reversibility and retrievability must be exist until final closure.[2]

Reversibility is closely associated with a decision-making model that has been summarized in the concept *stepwise decision-making*.[3] This model has been inspired by modern decision theory and was introduced in the context of retrievability by the OECD's Nuclear Energy Agency, NEA, and the Canadian Nuclear Waste Management Organization, NWMO. This decision model has long been accepted practice in the nuclear technology field[4] and it has also been important in the Council's treatment of the issue.[5]

Stepwise decision-making stands in contrast to older decision theory, where decisions on large engineering projects are made all at once, and where all detailed solutions are finalized from the start. According to the newer model, decisions are made stepwise, and each step is preceded by a review and a "go" or "no go" decision. This stepwise approach also provides opportunities for societal and political review, and allows for a gradual growth in confidence in the feasibility and safety of the facility, as information and experience are acquired.[6]

Thus, stepwise decision-making satisfies the need for flexibility in a process where the quantity of technical information is constantly increasing and changing. For example, the safety case for a repository will evolve as the site is characterized, the design is refined, and the understanding of features, events, and processes relevant to the performance of the repository is improved.[7]

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[2] SSMFS 2008:21 (formerly SKIFS 2002:1), Section 1, and the Swedish Radiation Safety Authority's general recommendations on Section 1.

[3] Also known as *SDM* or *adaptive phased management* (APM).

[4] The stepwise decision-making model was applied in connection with the licensing of the first nuclear power reactors. The most recent examples of stepwise decision-making in nuclear technology can be found in connection with the licensing of thermal power increases at several of Sweden's nuclear power reactors and Clab Stage II. The licensing of Clab II took about 10 years from submission of the expansion application to the authority until the plant could be put into routine operation.

[5] See KASAM's state-of-the-art report 2001, p. 9, p. 50 and p. 91.

[6] Reversibility and Retrievability, NEA, 2001, p. 11.

[7] Same source, 2001, p. 13.

The model for stepwise decision-making has had a great influence on spent nuclear fuel management in various countries, including Canada, France, Finland and the UK. When the British Committee on Radioactive Waste Management submitted its recommendations to the British Government in 2006, it was emphasized that

> … phased geological disposal and flexibility, possibly associated with retrievability, should be important elements in an adaptive phased process.[8]

3.1.2 Retrievability in different countries

The implications and desirability of retrieval have been judged differently in different countries. The following can be concluded from a recent study by the NEA:

- *Canada* uses the term "retrieval" to mean removal of nuclear waste from a repository both *before* and *after* closure – and this is also a requirement according to the principle of stepwise decision-making (see above).
- In *Switzerland,* retrievability is also an important requirement, but here the term only refers to retrievability *before* closure. Closure concludes the period during which the waste must be retrievable.
- In *Hungary,* the question of retrievability is not explicitly mentioned in the national legislation; however, government regulations require retrievability before closure – but not after.
- In the *USA,* the regulators require that a final repository be designed so that retrieval is not impossible, but post-closure retrieval is not envisioned here either.
- In *Germany,* retrievability is not mentioned either in legislation or in government regulations, but the topic has come up in the public discussion in recent years.
- In *the Netherlands,* retrievability was a topical issue in the mid-1990s. The official line there has been that retrievability should also be possible after closure. The Government at that time was therefore opposed to a final repository in salt formations, since such a repository would make retrieval virtually impossible.

[8] www.corwm.org.uk.

- *The UK* Government observed in 2006 that opinions differ on retrievability, but endorses the recommendations of CoRWM (Committee on Radioactive Waste Management) and says that steps to facilitate future retrieval should be taken before closure of the repository. The main principle is closure at the earliest possible opportunity in order to increase safety, limit the risks of terrorism and avoid exposing the workers in the final repository to harmful radiation doses.
- In *Japan* retrievability is not mentioned in the national legislation, but retrievability *before* closure is mentioned in official studies as one of the safety requirements.

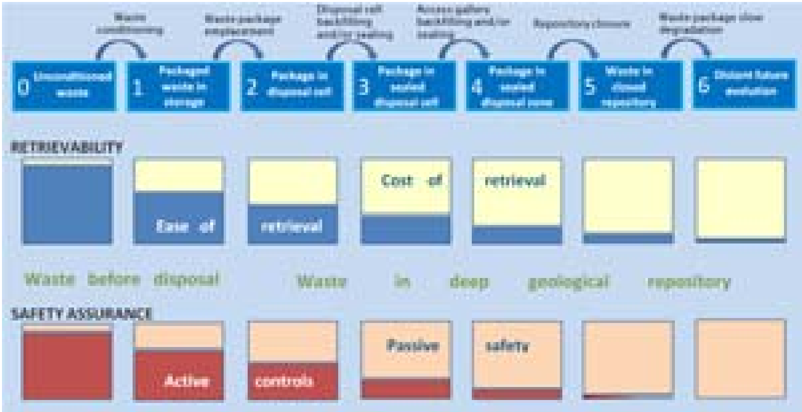
In this context there is special reason to take note of developments in two other countries, Finland and France.

- In *Finland,* retrievability was previously a legal requirement, but in 2008 the Government stated in a decision that long-term safety does *not* necessarily presume retrievability. This change will probably have an impact on STUK's (the Finnish Radiation and Nuclear Safety Authority) regulations, but is complicated by the existence of a parliamentary decision from 2000 that is based on the old legislation and that includes a requirement on retrievability (primarily pre-closure). The planned final repository in Olkiluoto is subject to this requirement.
- *France* has been a pioneer when it comes to retrievability. The question was discussed back in the 1980s and left its mark in the country's legislation in the early 1990s. This legislation was renewed in 2006 and includes a requirement on reversibility.

  The French discussion has been strongly influenced by the idea of stepwise decision-making, where reversibility is a general requirement that includes retrievability. The French National Radioactive Waste Management Agency[9] will, in its upcoming application for a permit to build a final repository, show how the reversibility requirement can be met, at least up to 100 years in the future. They are currently working to define this requirement in greater detail by 2014, before they submit their final application in 2015. This work includes constructing a "reversibility-retrievability scale", which is being further refined by an ad hoc group within the NEA (Figure 2).

[9] Agence nationale pour la gestion des déchets radioactifs, established 1991.

Figure 2 A reversibility-retrievability scale



Description: A reversibility-retrievability scale defines different milestones in the execution of a final repository project (0–5), the degree of difficulty and cost level of retrieval, and the degree of active/passive safety measures. The figure is under development by the NEA and is subject to change.

In some countries (for example France, Japan, Canada and the USA), retrievability is closely connected with the social acceptance of a final repository for spent nuclear fuel. Retrievability is considered to contribute to making final disposal of nuclear waste more acceptable and can be desirable for this reason. On the other hand, public acceptance must not be confused with long-term safety, and a distinction should be made between:

- retrievability as a social or political requirement,
- retrievability as a safety requirement, and
- retrievability as an ethical requirement, for example based on the principle of the freedom of choice of future generations.

We will examine this more closely in Chapter 3.

3.1.3 The trend in the NEA

Nor should the influence of international expert opinion be underestimated. It is most clearly manifested in a study conducted within the NEA and published in 2001 under the title “Considering Reversibility and Retrievability in Geologic Disposal of Radioactive

Waste".[10] The study results in a number of conclusions and recommendations which, in a guarded and cautious manner, open the door for retrievability. The NEA writes the following, for example:

> R&D should continue in technologies relevant to waste retrieval and, in particular, demonstrations of retrieval technologies should be encouraged in the various national and international research programmes. Such demonstrations contribute to technical confidence in the feasibility of waste retrieval and also to a wider non-technical confidence in the feasibility and the seriousness of the waste management organisations about retrievability.

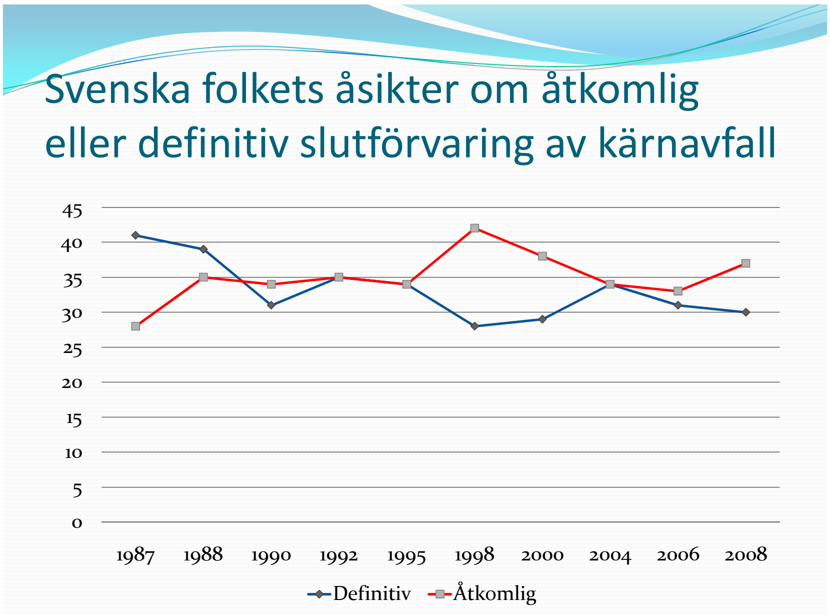
In this context it is of interest to note that in 2007 the NEA created an ad hoc group for the purpose of further examining the question of reversibility and retrievability. The group has had three meetings and is now planning a large international conference in Reims at the end of 2010.

3.1.4 Swedish attitudes to retrieval

Sociological studies conducted by the SOM Institute at the University of Gothenburg since 1987 testify to a shift in values among the general public when it comes to the value of retrievability (see Figure 3).

[10] NEA/RWM/RETREV(2001)2

Figure 3 Opinions of Swedish people on accessible versus permanent final disposal of nuclear waste during the period 1987–2008



At present, more people advocate accessible than permanent final disposal. This is particularly true of men and people under the age of 30, highly educated people and big-city residents. Women, people over 60, uneducated people and rural residents prefer permanent final disposal to accessible. Opponents of nuclear power prefer permanent final disposal to a greater extent, advocates to a lesser extent. One-third have no opinion.[11]

Public opinion on the accessibility of the nuclear waste was mentioned in the Council's state-of-the-art report from 2001. There it was observed that a shift has taken place in the discussion

> … **from** final repositories which would be closed and sealed and nobody would need to care about anymore **to** repositories from which it will be possible to retrieve the waste packages. In short, the previous attitude was based on technology while the later attitude is based rather on public perception.[12]

[11] *Svensk höst*, SOM-rapport nr 46, article by Per Hedberg, pp. 259–266.
[12] *Nuclear Waste. State-of-the-Art 2001*, SOU 2001:35e, p. 91.

3.2 Retrievability in the history of Swedish nuclear waste management

The issue of retrievability has so far not occupied a prominent position in the public discussion in Sweden. An explanation for this can be sought in the history of Swedish nuclear waste management.

An important milestone in the approach to management of the Swedish nuclear waste was reached in the report of the AKA Committee in 1976.[13] The question of retrieval of the spent nuclear fuel was not dealt with there, however; the report was completely focused on the question of a *final* disposal of the nuclear waste. The KBS method emerged in response to the report, and in 1983 KBS-3 was presented, and subsequently became the planning premise for all planning up until the present. In this context, the issue of retrievability became marginal.

It should, however, be emphasized that SKB has dealt with the issue on different occasions, including in its research and development programmes. They have always claimed that the KBS-3 method neither presumes nor excludes retrieval. This standpoint also finds support in the regulatory framework, as manifested in government regulations and general recommendations/guidelines (previously SKI's, now SSM's).

The discussion of retrieval in this publication presumes the KBS-3 method, since SKB's application will in all probability pertain to a final repository based on this method. But it should be pointed out that the prospects for retrievability and reversibility take on another dimension if a final repository is designed as one or more deep boreholes. One of the arguments for deep boreholes is that they make retrieval more difficult.

[13] *Spent Nuclear Fuel and Radioactive Waste*, SOU 1975:31

3.2.1 The Council's treatment of the retrievability issue

The Swedish National Council for Nuclear Waste has, on different occasions since the late 1980s, treated the issue of retrieval and retrievability of emplaced spent nuclear fuel. In 1987, the Council (then called KASAM) arranged an interdisciplinary seminar on *Ethics and Nuclear Waste*, with a special emphasis on the question of *decisions under uncertainty*. The KASAM principle was coined during this seminar:

> A final repository should be designed to render controls and corrective measures unnecessary, but not impossible.

In other words, our generation should not place the responsibility for the final repository on future generations, nor should we deprive future generations of the possibility of taking responsibility. The objective was therefore formulated as two-fold:

1. Operational reliability and reparability, controls unnecessary but at the same time possible.
2. Disposal under safe forms, but also with provision for change.

Two comments on the KASAM principle may be warranted.

In the first place, the KASAM principle challenges the widely held view that the post-closure repository *necessarily* needs controls. A distinction must be made between controls in the sense of measurements of the protective capability of the barriers and controls in the sense of external monitoring to make sure no unauthorized persons intrude into the repository. Controls of the protective capability of the barriers should not be necessary after closure, but external monitoring is a requirement from the IAEA[14] (see further below).

In the second place, retrievability follows from the KASAM principle. Among other things, future generations must be free to use and retrieve the nuclear waste as a resource. Provisions for retrieval should thereby be more clearly included in the requirement specification for the design of the repository.

For various reasons, the question of retrievability fell into obscurity during the 1990s. One such reason was that the Swedish Nuclear Power Inspectorate in its regulations and general recommendations/guidelines (see Appendix 1) gave priority to safety as the most important performance criterion for a final repository for

[14] International Atomic Energy Agency.

nuclear waste. SKB therefore changed its terminology in the mid-1990s from “deep repository” to “final repository”. This emphasizes that the repository should not require any monitoring or controls and that a retrieval of the emplaced fuel is not foreseen either.[15]

Despite the intention manifested in SKB’s change of terminology, the question of retrievability did not arise again until the late 1990s. One reason for this was international developments within the IAEA and the OECD, but a change in values was also noticeable in Sweden in the late 1990s. The reasons behind this change are unclear, but one possibility is the emergence of a more positive attitude to nuclear power as an energy source.[16]

3.2.2 SKB’s attitude

In its review of SKB’s 2004 research, demonstration and development programme, the Swedish National Council for Nuclear Waste pointed out the necessity of analyzing safety in connection with a possible retrieval of fuel canisters from the final repository. No such analysis has as yet been presented by SKB, but has been envisioned as a system variant in a future system analysis.[17] In its RD&D programme 2007, SKB notes that there is no formal requirement that it should be possible to retrieve deposited canisters after repository closure, but at the same time states the following:

> However, SKB has formulated its own requirement that the final repository must be designed in such a manner that it is possible to

[15] The Government’s special advisor in the Swedish National Council for Nuclear Waste, Olof Söderberg, explained in a report the distinction between a deep repository and a final repository in the following manner: “By deep repository is meant a facility at great depth in the rock that can meet the requirements of the Nuclear Activities Act on permanent storage (final disposal) of nuclear waste in a safe manner while also providing for the possibility of retrieval. Disposal of nuclear waste in a deep repository thus does not rule out other solutions in the future. It can therefore be regarded as a form of interim storage that must meet the requirements now made on final disposal. Not until a decision is made in the future to close the deep repository can it be said that the storage of the fuel there is intended to be permanent, i.e. that storage now becomes final disposal in the sense of the Nuclear Activities Act”. SOU 1999:45.

[16] In 1999 the Swedish National Council for Nuclear Waste, in cooperation with the IAEA, arranged an international seminar on retrievability in Saltsjöbaden. A number of international experts participated in this seminar, and the status of the retrievability requirement in different national nuclear waste projects was discussed. Other topics that were treated were popular acceptance, ethical aspects, controls and monitoring. The seminar was documented in a detailed report (*Retrievability of High Level Waste and Spent Nuclear Fuel*, IAEA-TECDOC-1187, 2000) and in the Council’s state-of-the-art report 2001.

[17] RD&D programme 2004, p. 370.

> retrieve deposited canisters before closure. This may not lead to technical designs that compromise the long-term performance of the repository, however. Single canisters may have to be retrieved from a deposition hole if something unforeseen happens during deposition. Retrieval of a large number of canisters in a later phase of operation of the repository must also be possible. If another method for disposing of or making use of the spent nuclear fuel is preferred in the future, technology for retrieving canisters will be needed then as well.[18]

SKB's basic attitude could be formulated by saying that retrieval of the deposited nuclear waste should not be necessary, but not impossible either. However, the RD&D programmes do not mention any extensive measures to facilitate this possibility.

SKB does in its most recent programme describe a successful attempt to free a copper canister of natural size using makeshift equipment in the Äspö HRL. But this experiment does not appear to be founded in any well-thought-out theoretical considerations, and no other provisions for pre- or post-closure retrieval are mentioned. It should, however, be noted that the neither the regulatory authorities nor the Swedish National Council for Nuclear Waste have made any critical comments on this. In its most recent reviews (2005 and 2008), SKI did not express any objections to SKB's handling of the retrievability issue, but limited itself to citing its regulations and general guidelines.[19]

In summary, the main impression is that retrievability has been accorded relatively marginal importance in the final repository project and that the responsible authorities are largely OK with this. It would appear that this is the policy that will be embodied in the application for a permit to build a final repository that SKB expects to submit at the end of 2010. This is also in line with the purpose formulated by SKB in its application for a permit to build an encapsulation plant in 2007:

- SKB's purpose is to build, operate and close a final repository with a focus on safety, radiation protection and environmental considerations.
- The final repository is being designed to prevent illicit tampering with nuclear fuel both before and after closure. Long-term safety will be based on a system of passive barriers.
- The final repository is intended for spent nuclear fuel from the Swedish nuclear reactors and will be created within Sweden's

[18] RD&D programme 2007, p. 208.
[19] See for example SKI 2008:48 E, p. 97.

boundaries with the voluntary participation of the concerned municipalities.

- The final repository will be established by those generations that have derived benefit from the Swedish nuclear reactors and designed so that it will remain safe after closure without maintenance or monitoring.

A few things should be noted here. *In the first place,* it can be concluded that retrievability is not a prerequisite (despite the fact that SKB has "formulated its own requirement that the final repository must be designed in such a manner that it is possible to retrieve deposited canisters before closure")[20]. *In the second place,* SKB refers to the aforementioned KASAM principle and asserts that the repository will be safe even without maintenance and monitoring. But the mere possibility of retrieval entails a number of international obligations, for example in accordance with the IAEA's regulatory system to guard the repository and make sure no one tries to enter it unlawfully.[21]

The Council's *State-of-the-Art Report 2001* notes the following:[22]

> It is obvious that if we conclude that the waste in a deep geological repository is retrievable – even if a real retrieval would be a large and costly undertaking – then we have also concluded that the material is not in practice impossible to recover, and will therefore be subject to continued safeguards.[23].

The safeguards system (i.e. a system for maintaining control of nuclear materials) which Sweden has undertaken to participate in also makes other requirements on a final repository with provision for retrieval. A reliable method is needed for identifying the canisters that are retrieved, and the marking of the canisters must be durable in the long-term perspective.[24]

[20] SKB's RD&D Programme 2007, p. 208.
[21] These obligations are summarized in the SAGOR programme (SAGOR – Programme for the Development of Safeguards for the Final Disposal of Spent Fuel in Geologic Repositories).
[22] SOU 2001:35, p. 59.
[23] Hereinafter we will designate "safeguards" as protection and protective systems.
[24] This is emphasized by SKB in RD&D 2007, where it is also said that the information on the contents of the canisters must meet the same requirements (RD&D 2007, p. 98).

3.3 Retrieval technology in the 21st century

As has already been mentioned, SKB has carried out a practical retrieval experiment in recent years. The experiment has been carried out in the Äspö HRL, and according to SKB it has shown that it is possible in practice to free a canister from saturated bentonite and carry out a retrieval. This has been done using a hydrodynamic method, where the bentonite is slurried with salt water and pumped away. The method can be time-consuming, but no major difficulties have been identified.

The Swedish National Council for Nuclear Waste finds that while the retrieval experiment has yielded new and important knowledge, the value of the experiment is limited by the fact that it has not been carried out with a canister that has been heated in the manner foreseen in connection with a realistic retrieval some time before the final closure of the repository. The experiment was also done with vertical deposition, which provides unsatisfactory guidance for retrieval of horizontally deposited canisters – assuming SKB chooses such an emplacement of the canisters.

Certain retrievability tests have been performed abroad, for example at the American final repository for military nuclear waste in southeastern New Mexico[25] in 2007–2008. The repository is situated in a salt formation at a depth of about 700 metres. A decision was made to retrieve a waste container due to unsatisfactory documentation of its contents and the retrieval was successful. There are also other examples of successful retrievals of nuclear waste, for example in Dunrey, Scotland.

Knowledge concerning retrievability has grown in recent decades, but what is lacking in the Swedish programme is a more systematic plan for different phases and different parts of the final repository.

Previously we noted that a large majority of the Swedish people prefer an accessible final repository. The design of a future final repository can naturally not be decided on the basis of opinion polls, but observation is relevant when technical and ethical arguments point in the same direction as public attitudes. The Swedish National Council for Nuclear Waste would therefore like to make an overall assessment of the technical and ethical arguments, and against this background summarize its position in four points.

[25] WIPP, Waste Isolation Pilot Plant.

3.3.1 Is retrieval technically feasible?

As far as the technical feasibility of retrieval is concerned, there is no reason to doubt SKB's general assessment that the KBS-3 method permits retrieval both before and after final closure of the repository. The Canister Retrieval Test in the Äspö HRL may not provide fully adequate guidance, but the slurrying technique used appears to be a workable method.

Retrieval *after* closure will naturally be technically more difficult and more costly.[26] Post-closure retrieval will be particularly costly if the existing final repository should for some reason not be deemed sufficiently safe. If, on the other hand, retrieval is carried out to make use of the nuclear waste, the benefit can offset the burden. Purely technically it is a question of a traditional mining operation; the canisters are then assumed to be intact and able to be freed in a manner illustrated in the Canister Retrieval Test in 2007.

3.3.2 Is retrieval legal under civil law?

Aside from the technical feasibility, we have the question of its *legality* under civil and bankruptcy law. Current legislation regulates in detail who is responsible for the final disposal of spent nuclear fuel and other radioactive waste. The reactor owners are responsible for the safe final disposal of the spent nuclear fuel and the nuclear waste.

The reactor owners have commissioned SKB to dispose of the spent nuclear fuel and the nuclear waste. SKB's responsibility entails designing the final repository in such a way that the spent nuclear fuel and the nuclear waste can be disposed of in a safe manner. SKB also has a responsibility[27] to ensure that Sweden's obligations under treaties aimed at preventing the proliferation of nuclear weapons and unauthorized dealings with nuclear material and spent nuclear fuel are fulfilled even after closure of the final repository. On the other hand, the reactor owners cannot transfer ultimate responsibility for final disposal of the spent nuclear fuel, but must themselves be active in ensuring that the safety of the final repository meets very high standards.

[26] IAEA TECDOC-1187, p. 189–201.
[27] Sections 3 and 4 of the Nuclear Activities Act.

The reactor owners' or SKB's responsibility under the Nuclear Activities Act thus lasts until it has been fulfilled, which, according to the Nuclear Activities Act, occurs when the final repository for spent nuclear fuel and other radioactive waste has been finally closed[28].[29] A reactor owner whose reactor has been shut down permanently can then discontinue his activities and cease to be a legal entity. SKB's responsibility can last even longer. After SKB has fulfilled its obligations under the Nuclear Activities Act by finally sealing the final repository and closing it against intruders, SKB still has a responsibility under the Environmental Code as an activity operator for remediation of any damage to the environment or other damage caused by the final repository.

By ratifying the 1997 Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (the Nuclear Waste Convention), the Swedish state has undertaken ultimate responsibility[30] for the safety of final disposal. Ultimate responsibility entails that if there for some reason should not be any licensee or other responsible party who is capable of bearing responsibility for the final repository or refrains from doing so for other reasons, the ultimate responsibility for safety rests with the state. The state's ultimate responsibility should also entail that the state, via an authority, exercises control over the area by monitoring. Via the IAEA and the European Commission, there is also an international interest in ensuring that the state provides some kind of supervision of the waste itself and physical protection of the area.

When the state's ultimate responsibility comes into play, it may also be appropriate for title to the property or properties where the final repository is located, as well as title to the spent nuclear fuel, to pass to the state as well. This cannot simply be assumed, however. The encapsulated spent nuclear fuel in the final repository has considerable value that could be realized in the future. The state's ultimate responsibility is limited to the safety of the final repository. However, there may be other stakeholders, for example the parent companies of the corporate groups to which former licensees may have belonged or future property owners, who wish to lay claim to title to the spent nuclear fuel.

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[28] See Gov. Bill 2005/06:183, p. 30 and SOU 2009:88, p. 424.
[29] Section 14 of the Nuclear Activities Act.
[30] According to Article 21 of the Convention, ultimate responsibility entails that the state is forced to assume a purchasing and financing role if the nuclear power industry is not able to carry out the task or refrains from doing so for other reasons.

One question that has come up in this context concerns the case when a reactor owner has deposited all his spent nuclear fuel and these parts of the final repository have been sealed before other reactor owners' fuel has been deposited and the final repository is finally closed. This reactor owner can then be considered to have fulfilled his obligations and is therefore discharged from them according to the Nuclear Activities Act. He may then also have objections if any of the other reactor owners has plans to retrieve previously deposited fuel.

Another question that can complicate the picture is if one of the companies that has deposited fuel in the final repository, or even SKB, should go bankrupt. What claims on property – for example real estate or spent nuclear fuel – can the state and other companies who have deposited spent nuclear fuel in the final repository make against the bankruptcy estate or the bankrupt?

There are thus several actors who could have an interest from different perspectives in the question of retrieval of the deposited fuel. Thus, in addition to the question of the technical feasibility of retrieval, the legislation in effect at the time has a bearing on the legality under civil law of retrieval of the deposited fuel by the future actors.

Finally, if any actor should wish to retrieve the deposited fuel after the final repository has been closed, a new licensing of the activity is required under both the Nuclear Activities Act and the Environmental Code.[31]

3.3.3 Is retrieval/retrievability desirable?

The technical question of the *feasibility* of retrieval (before or after closure of the repository) differs from the ethical question of its *desirability*. In *Considering Reversibility and Retrievability*, a summary is given of the most common arguments for and against retrievability provisions (i.e. measures to facilitate retrieval).[32] Four different arguments are distinguished here that *favour* waste retrieval provisions:

[31] According to its terms of reference, the Committee for a Coordinated Regulation of Nuclear Technology and Radiation Protection (M 2008:05) should consider legislation to regulate the ultimate responsibility of the state and other actors for the final repository for spent nuclear fuel.
[32] *Considering Reversibility and Retrievability in Geologic Disposal of Radioactive Waste*, pp. 17–21, NEA/RWM/RETREV(2001)2.

- Technical safety concerns that are only recognized after waste emplacement and/or changes in acceptable safety standards.
- A desire to recover resources from the repository, e.g. components of the waste itself, or the recognition or development of some new resource or amenity value at the site.
- A desire to use alternative waste treatment or disposal techniques that may be developed in the future.
- To respond to changes in social acceptance and perception of risk, or changed policy requirements.

At the same time, there are arguments opposing waste retrievability provisions. They include:

- Uncertainty about negative effects, including conventional safety and radiological exposure of workers engaged in extended operations and/or associated monitoring, or marginal gains.
- The possibility of failure to seal a repository properly due to the adoption of extended or more complex operational plans to favour retrievability.
- The favouring of irresponsible attempts to retrieve or interfere with the waste during times of political and/or social turmoil when safeguards and monitoring features are no longer in place.
- A possible need for enhanced nuclear safeguards – possibly at the price of making retrieval more difficult.

The reasons *in favour* of retrievability provisions can be simply summarized with the words: *flexibility* and *reversibility*. Reversibility opens up possibilities for coping with more or less probable future events. Flexibility is also a principal ingredient in the stepwise decision model.

The reasons *against* retrievability provisions can similarly be summarized in the words *long-term safety*. If extensive retrievability provisions are built into the final repository, this may have negative consequences for the safety of the repository – especially if it leads to requirements to refrain from or postpone closure of the repository to facilitate retrieval.

However, the Swedish National Council for Nuclear Waste has concluded that arguments in favour of retrievability provisions must be weighed against the disadvantages:[33]

> Does the adaptation of the final repository for possible retrieval necessitate certain compromises with regard to long-term safety? The question is an ethical one. What should be prioritized? The freedom of choice of future generations or their safety?

To this the Council would now like to add two clarifications:

1. Provisions for post-closure retrieval may conflict with the requirement of long-term safety. Whether this is actually the case or not is of course another question. According to some, there is nothing to say that a final repository that meets stringent requirements on long-term safety could not also meet the requirement on retrievability.
2. As far as flexibility, reversibility and retrievability *before* closure are concerned, it appears to be easier to combine these performance criteria with the requirements on both short- and long-term safety. As is evident from the previous review of the international trend, there is a growing consensus that the possibility of retrieving one or more canisters from a repository is commensurate with the requirements on both safety and respect for the freedom of choice of future generations.

Against this background, the Council would like to formulate some summarizing and more concrete arguments for raising the status of the principles of reversibility and retrievability in the Swedish final repository project.

3.4 Conclusions of the Swedish National Council for Nuclear Waste

Developments in recent decades have not diminished the urgency of retrievability, rather the contrary. The attitudes of the Swedish people have changed, and considerations in other countries and in international bodies warrant a re-examination of the question. Furthermore, in the opinion of the Council there are technical future scenarios that have lent weight to the requirement on retrievability. In conclusion, the Council would like to briefly

[33] Nuclear Waste. State-of-the-Art Report 2004, SOU 2007:38, p. 61.

describe these scenarios and what bearing they have on the issue of retrievability.

1. The Swedish National Council for Nuclear Waste has in previous state-of-the-art reports noted that technologies may be developed in the future to make the waste less long-lived than it is today. By means of partitioning and transmutation (P&T), the radioactive substances could be bombarded with neutrons, shortening their storage time to less than 1,000 years, compared to the hundreds of thousands of years for which the present-day waste remains harmful to biological life.

   The Council's conclusions in 2004 were:[34]

   > The application of P&T (partitioning and transmutation) to Swedish nuclear waste will be a question for future generations. With present-day knowledge of this technology, it is not acceptable to interrupt or to postpone the Swedish nuclear power programme, citing P&T as an alternative. On the other hand, this possible future alternative reinforces the requirement that the repository should be designed so that waste retrieval is possible. According to the ethical principles that the Riksdag has established, each generation should take care of its own waste and not force future generations to develop new technologies to solve the problems. Therefore, it is reasonable for resources to be put aside for further research on P&T. This research could also pay off in ways which are of value for other areas, such as nuclear physics, chemical separation technology and materials technology. Swedish P&T research should be coordinated with the research and development being conducted in other countries. To allocate resources for further P&T research at this stage is also in line with the view that our generation should give future generations the best possible opportunities to decide whether they want to choose P&T as a method for disposing of spent nuclear fuel, instead of direct disposal alone (in accordance with the KBS-3 method, for example.[35]

   The Swedish National Council for Nuclear Waste finds no reason to depart from this judgement and wishes to once again emphasize this underlined sentence that P&T is a possible future alternative that reinforces the requirement that retrieval should be possible. Furthermore, the Council wishes to add that it is urgent for the current generation to set aside additional

[34] Swedish National Council for Nuclear Waste's State-of-the-Art Report 2004, SOU 2004:67, Chap. 8.
[35] Same source, pp. 408–409.

resources for such P&T research, since it could radically reduce the long-term toxicity of the nuclear waste.

2. New perspectives have opened up in recent years when it comes to the possibilities of using the high-level waste as an energy source. Fourth-generation nuclear power reactors are currently under development, and a demonstration plant is expected to be built somewhere in Europe around 2020. This type of reactor could transform the long-lived waste and make use of its energy. Professor Ane Håkansson predicts that there may be commercial fourth-generation reactors in operation by around 2040–2050.[36] But getting there won't be easy. Among other things, the new reactors require reprocessing of the spent nuclear fuel. A special reprocessing plant would have to be built, which would require international cooperation within, for example, the EU. Uranium would be separated from plutonium in such a facility, which could conflict with the desire to prevent nuclear weapons proliferation. But an advantage is that the fourth-generation reactors can use other types of fuel than uranium, for example thorium, which is not suitable for nuclear weapons production.

   It is not the task of the Swedish National Council for Nuclear Waste to take a stand on new reactor technology or the desirability of a new nuclear power programme. The Council can, however, observe that this technology is one of the future scenarios we may have to consider. Like P&T, the emergence of such a future scenario reinforces *the requirement that the repository should be designed so that waste retrieval is possible without jeopardizing long-term safety.*

3. The Swedish National Council for Nuclear Waste would also like to draw attention to another future scenario, which is associated with even greater uncertainties and is even more remote in time. This future scenario is fusion power. Instead of splitting atomic nuclei as in the case of nuclear power, nuclear fusion extracts energy by joining or fusing atomic nuclei to form new elements, for example fusing hydrogen nuclei to helium. This is how the sun produces its energy. The problem is that fusion can only be achieved at very high temperatures – several million degrees. At such temperatures the materials assume another state: plasma. In a fusion reactor, this plasma is held in place by

[36] UNT, 5 November 2009.

a powerful magnetic field. So far no one has managed to build a reactor that generates more energy than is required to initiate, sustain and control the fusion reaction. There are, however, currently several different international research projects in the field, and a research reactor is planned to be built in Cadarache, France, which is expected to be operational in the 2020s. Another type of reactor – Wendelstein 7X – is under construction at the Max Planck Institute in Greifwald.

4. According to SKB's calculations in Plan 2008, the final repository will be ready to receive the first canister in 2023 and the last around 2054 (assuming a reactor operating time of 40 years) or 2069 (reactor operating time 50–60 years). This will be followed by repository closure. SKB has calculated that closure will take place sometime between 2069 and 2084. According to other estimates, closure will not take place until 2100.[37] The possible emergence of new technologies for processing of the spent nuclear fuel and the development of the fourth generation of nuclear reactors are two examples of circumstances that could influence the design of the final repository before or after closure. Such circumstances generally impose requirements on reversibility. But of course there are also many other events that could warrant going back one or more steps in the process. Reversibility could in some situations entail retrieval of one, several or all the canisters deposited in the repository.

Reversibility is a crucial element in the model for stepwise decision-making referred to at the beginning of this chapter and is also a result of the requirements specified in SSM's regulations.[38] The Swedish National Council for Nuclear Waste assumes that SKB will in its upcoming application shed light on the consequences of this requirement on reversibility and stepwise decision-making in different phases of the execution of the final repository project. More clearly than before, the Council wishes to emphasize today that provisions for pre-closure retrieval have the potential to strengthen the final repository's long-term safety. Pre-closure retrieval may be considered for several different reasons. One or more canisters may need to be retrieved due to design flaws revealed after emplacement. A number of copper canisters may need to be moved to other

[37] *Statens ansvar för slutförvaring av använt kärnbränsle*. SKI Rapport 2007:01, SSI Rapport 2007:01, p. 50.
[38] SSMFS 2008:21 (formerly SKIFS 2002:1), Section 1, and the Swedish Radiation Safety Authority's general guidelines on Section 1.

deposition holes in another deposition tunnel. Some – or all – canisters may need to be retrieved in order to reuse the nuclear fuel in some form. *In the opinion of the Council for, reversibility is a performance criterion worthy of consideration for a future final repository.*

In summary, the Swedish National Council for Nuclear Waste finds that retrievability is an important part of pre-closure reversibility as well as an important factor in winning the public's confidence. However, the Council is not yet prepared to accede to demands that entail postponing repository closure. While there may be circumstances where such postponement could be considered, the Council would like to emphasize that the demonstration period should not be extended further than is warranted to prove the reliability of the final repository.

Two crucial reasons for this are that uncertainties always exist regarding the future evolution of society, and that completion of the final repository project on schedule is an important prerequisite for not placing unfair burdens on future generations.

Reversibility as a performance criterion for a future final repository refers primarily to pre-closure retrievability. Such reversibility is a part of the safety requirement and is commensurate with consideration for the freedom of choice of subsequent generations. After final closure of the repository, safety- and safeguard-related considerations must be given priority over the principle of freedom of choice of future generations.

Furthermore, even if it is technically feasible, post-closure retrieval is both controversial and complicated from a civil law perspective. The spent nuclear fuel has a complicated ownership structure, and there are several actors who may have an interest in the question of waste retrieval from different perspectives. Besides the technical feasibility of the project, the legislation in effect at that time will determine whether the future actors will be legally entitled to retrieve the waste. If any actor should want to retrieve the deposited fuel after closure of the final repository, a new licensing of the activity is required under both the Nuclear Activities Act and the Environmental Code.

Appendix

Legislation and government regulations

According to the Nuclear Activities Act (1984:3), Section 3, nuclear activities shall

> … be conducted in such a manner that safety requirements are met and the obligations entailed by Sweden's obligations under treaties aimed at preventing the proliferation of nuclear weapons and unauthorized dealings with nuclear material and nuclear waste consisting of spent nuclear fuel are discharged.

Hence, the legal text have an *indirect* bearing on retrievability but does not contain any special provisions on retrievability. Safety in such activities shall be maintained by adopting measures to

> … prevent unlawful dealings with nuclear material or nuclear waste. (Section 4)

Furthermore, it can be noted that the law uses the term "final repository" and that licensees are responsible for

> … ensuring the safe management and final disposal of nuclear waste arising in the activities or nuclear material arising therein that is not reused. (10 §)

This of course does not exclude the possibility that a final repository may be designed with reasonable provisions for retrieval before or after closure, nor that a final repository could be designed so that unlawful dealings with nuclear waste can be prevented without rendering retrieval impossible.

The regulatory framework for nuclear waste management was formulated in greater detail in the late 1990s by the Swedish Nuclear Power Inspectorate (SKI) and was adopted without any decisive changes by the Swedish Radiation Safety Authority (SSM) in 2008 in *the Swedish Radiation Safety Authority's Regulations and*

Guidelines on the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste (SSMFS 2008:37, formerly SSIFS 1998:1 and SSIFS 2005:5). Of particular importance are the formulations in Sections 8–9. There it says (under the heading "Intrusion and Access"):

> **Section 8** A repository shall be primarily designed with respect to its protective capability. If measures are adopted to facilitate access or hinder intrusion, the effects on the protective capability of the repository shall be described.
>
> **Section 9** The consequences of intrusion into a repository shall be described for the different time periods specified in Sections 11–12. The protective capability of the repository after intrusion shall be described.

SSM has also issued Regulations and General Recommendations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste (SSMFS 2008:21, formerly SKIFS 2002:1). There it says the following in Section 8 of the regulations and in the general recommendations on the same section:

> **Section 8** The impact on safety of such measures that are adopted to facilitate the monitoring or retrieval of disposed nuclear material or nuclear waste from the repository, or to make access to the repository difficult, shall be analyzed and reported to the Swedish Radiation Safety Authority.

In its general recommendations, SSM adds some recommendations on Section:

> Measures can be adopted during construction and operation for the possible monitoring of a repository's integrity and its barrier performance after closure. Such measures can also be adopted to maintain safeguards. Measures can also be adopted during construction and operation with the primary aim of facilitating the retrieval of deposited nuclear materials and nuclear waste from the repository, during the operating period or after closure. Furthermore, measures can be adopted to make intrusion into the repository difficult or to warn against intrusion. The safety report for the facility in accordance with Section 9 should show that these measures either have a minor or negligible impact on repository safety, or that the measures result in an improvement of safety, compared with the situation if the measures had not been adopted. These provisions are in agreement with the provisions of the *Swedish Radiation Protection Authority's regulations and guidelines* SSMFS 2008:37 (formerly SSIFS 1998:1 and SSIFS 2005:5).

Provisions for retrievability may be made, but the repository's protective capability is the primary consideration. If access (for example for retrieval) is facilitated or hindered, the effects of this on the repository's protective capability shall be reported. This does not exclude the possibility of retrieval, but it does not comprise a necessary performance criterion.