

Nuclear Waste State-of-the-Art Report 2011

—geology, barriers, alternatives

Report from the Swedish National Council for Nuclear Waste, Stockholm 2011



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*The Swedish National Council
for Nuclear Waste Report*

Stockholm 2011



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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 state of the art 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 eleventh in this series) entitled Nuclear Waste State-of-the-Art Report 2011 – geology, barriers, alternatives (SOU 2011:14).

During the year the Swedish National Council for Nuclear Waste has carried on discussions with actors in the Swedish final repository programme, followed the development of other countries' final repository programmes, and conducted a survey of which areas need to be further elucidated prior to SKB's application. The result is this year's state-of-the-art report, which sheds light on the geological premises for SKB's site selection, follows up last year's theme regarding the engineered barriers (the copper canister and the buffer), and sheds light on the alternatives issue from the legal, technical and social science perspectives. In addition, the council intends to return during the year with a special study regarding the role of the safety assessment during the final repository's different phases.

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, 2007 and 2010 are also available.

Stockholm, 14 February 2011

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1 Introduction

2010 was the last year before the licence application for a final repository for spent nuclear fuel is expected to be submitted to the Swedish Radiation Safety Authority (SSM) and the environmental court. This has dominated Swedish nuclear waste activities as well as the work of the Swedish National Council for Nuclear Waste during the year.

At the same time it is particularly important that the discussions not be limited to SKB's application and the method SKB has chosen (the KBS-3 method). Until the Government has made a decision on the application for the final repository for spent nuclear fuel, it is the Council's responsibility to continue to identify and investigate issues of importance for the final repository for spent nuclear fuel, and to contribute to an open discussion that also takes into account perspectives not directly included in SKB's application.

1.1 Role and responsibility of the Swedish National Council for Nuclear Waste

During the past year, the Swedish National Council for Nuclear Waste has worked to clarify the Council's role and mission to the Government, not least in connection with the processing of SKB's application¹.

According to the Government's terms of reference, the Council for shall advise the Government on matters relating to nuclear waste and the decommissioning and dismantling of nuclear facilities. The Council's target groups are the Government, concerned authorities, the nuclear power industry, municipalities, interested

¹ The Council's role and responsibility in the review of SKB's application is clarified in the document "Kärnavfallsrådets roll och ansvar" (in Swedish only), which can be downloaded on the Council's website: www.karnavfallsradet.se

organizations and politicians, the mass media and interested private citizens.

The Council interprets its mission as an adviser in the following way: Within the framework of its scientific expertise, the Council shall clarify the arguments in issues that are of central importance to the Swedish final repository programme – and sometimes controversial – as well as which issues the Council considers relevant in different areas. The Council shall be clear and visible in its role as an informed conversation partner and source of knowledge for the Council's target groups.

During the work with SKB's application, the council shall supplement SSM's review. SSM shall review the application according to the requirements in the the Nuclear Activities Act and the Radiation Protection Act. The Council can also bring up other issues such as broader societal, legal and ethical issues as well as environmental scanning, and discuss and elucidate issues from a non-regulatory perspective as well, for example by broadening the discussion of copper corrosion and buffer.

1.2 Conclusions of the Swedish National Council for Nuclear Waste

The Council has identified issues that are controversial and in need of further elucidation. These issues are elucidated in the three chapters of the state-of-the-art report:

- Chapter 1 presents the Council's assessment of SKB's reported findings concerning the geological premises for site selection in Forsmark and Laxemar.
- Chapter 2 follows up the Council's account and study of the engineered barriers: the copper canister and the bentonite.
- Chapter 3 deals with legal, technical and social science perspectives on the issue of alternative methods to KBS-3.

A brief summary of the Council's conclusions is presented here.

1.2.1 Geological premises for site selection

The conclusion drawn from a study of the geological premises for site selection is that good knowledge exists regarding the composition of the bedrock in both Forsmark and Laxemar.

The dominant rock type in Forsmark has a relatively high quartz content, which provides good thermal conductivity so that the deposition area can be made smaller than in Laxemar. In Forsmark, the bedrock also possesses good strength and the risk of major earthquakes is low. Knowledge of the large-scale structural evolution of the bedrock in both Forsmark and Laxemar is good, but there is greater uncertainty in Laxemar regarding the occurrence and extent of major and minor deformation zones and other structural elements.

The bedrock east of the investigation area in Forsmark is potentially ore-bearing and should be more thoroughly investigated. The occurrence of ores in the vicinity of Forsmark could entail a long-term safety risk (risk of intrusion). This problem does not exist in the Laxemar area. There is also a certain lack of knowledge in the hydrogeological models. In order to reduce the uncertainty in the models for Forsmark, it is recommended that a denser network of seismic profiles be carried out.

The alternatives have largely been identified on the basis of democratic principles inasmuch as the site investigations have been conducted in municipalities that have voluntarily participated in the process. The Council believes that voluntary participation is an important principle in the site selection process. At the same time, the Council notes that the detailed geological knowledge that now exists of these areas is unmatched in other parts of the country.

1.2.2 Durability of the barriers in the final repository environment

The engineered barriers (copper canister and bentonite buffer) are important guarantors of the long-term safety of the final repository for high-level spent nuclear fuel. In last year's state-of-the-art report, the Council described the background and issues associated with research results on corrosion of copper in water and erosion of bentonite in buffer and backfill. In this year's state-of-the-art

report, the Council recounts what has happened in this respect during 2010 and offers further viewpoints on the research that is being conducted.

The copper canisters

Thermodynamic calculations show that metallic copper can react in water in the presence of sulphur-containing ions, even under oxygen-free (anoxic) conditions. This means that the canister cannot be regarded as a completely independent barrier, but that long-term safety is also dependent on whether the bentonite buffer can protect the canister from prolonged direct contact with the groundwater. Although this is not an unknown phenomenon, it emphasizes the importance of preserving the bentonite buffer more or less intact in the repository.

In the Council's opinion, it is valuable for SKB to continue its research on copper corrosion in contact with water under both oxic and anoxic conditions (conditions with and without oxygen). The Council considers the corrosion mechanisms for copper under oxygen-free conditions to be of particular interest, since these are the conditions that will ultimately prevail in the repository. Studies under repository-like conditions are very valuable, not least with incomplete and uneven water saturation of the bentonite. In the Council's opinion, the research should not be limited to pure oxygen-free water, but should also include ions in the groundwater that can stabilize the copper oxidation products that are formed in the process. This applies in particular to different types of sulphur-containing anions and chlorides.

In-depth studies of stress corrosion cracking and how the strength of copper is affected by hydrogen absorption continue to be urgent. Creep in the copper metal that causes deformations of the copper canister may be a problem in the final repository due to the fact that the canister is subjected to high stresses and a corrosive environment. There is a need for continued research in this area.

Thus, the copper canisters cannot be expected to remain stable over the long term in the repository under conditions that entail that the canister is in constant contact with the corrosive ions in the groundwater. The properties of the bentonite as a barrier are therefore critical for long-term safety.

Processes in the bentonite

In the opinion of the Swedish National Council for Nuclear Waste, further research on the properties of the bentonite for specific use in the final repository is needed. This applies to bentonite in the form of compacted blocks, rings and pellets in both buffer and backfill. The composition of the bentonite buffer influences a number of mechanical and chemical properties, and the Council has in previous reports urged SKB to study and describe these properties in greater detail. Other important factors for optimizing the properties of the buffer include the pretreatment to which the bentonite is subjected before it is placed in the repository.

The water saturation of the bentonite is an important parameter for the future function of the buffer (strength and other chemical/physical properties) and should also be an topic for SKB's continued development efforts.

The Council notes that studies have been done where the bentonite has repeatedly been allowed to freeze and then thaw again. The Council recommends that similar experiments be done with contaminated groundwater and that any changes in the properties of the bentonite be recorded.

1.2.3 Legal, technical and social science perspectives on the alternatives issue

The main purpose of this section is, in relation to the Council's preceding state-of-the-art report², to present new knowledge concerning alternative methods from the legal, technical and social science perspectives.

From the legal perspective, greater importance must be attached to a description of alternative methods of nuclear waste disposal. An acceptable environmental impact statement is a prerequisite for examination of the licence application. In a judgement from 2009, the Supreme Court explained that an environmental impact statement is not acceptable if the alternative designs presented during the consultation process have not been described in the environmental impact statement. According to the Supreme Court, a minimum requirement is that the applicant describe different options

² Nuclear Waste State-of-the-Art Report 2010 – challenges for the final repository programme. SOU 2010:6.

and explain why an alternative has not been further pursued and state on what grounds the applicant has arrived at the conclusion that there are no alternatives.

Certain technical and scientific advances have been made when it comes to Deep Boreholes and Partitioning and Transmutation. However, there is no method today that can compare with KBS-3 in terms of the current state of knowledge, and the Council considers that further research is needed to evaluate whether Deep Boreholes is an alternative for final disposal. Partitioning and Transmutation does not eliminate the need for a geological repository, but will lead to changed requirements on the engineered barriers. Technological developments in the field of reactor physics and nuclear fuel will be of crucial importance for the waste that will be generated.

The issue of alternatives in planning and decision-making for a final repository for spent nuclear fuel clearly shows the need for both technical and social science research independent of the immediate needs of the activity operator. The Council believes it is very urgent that resources be created to stimulate critically reflective social science research on the nuclear waste issue and the premises for planning and decision-making.

In the Council's opinion, formulation and evaluation of different alternatives to the KBS-3 method is of vital importance for compiling a reliable body of data to permit a safe and socially legitimate solution to be found to the nuclear waste issue.

2 Geological premises for site selection

In June 2009, SKB announced its selection of Forsmark as the site for the final repository spent nuclear fuel. The final choice stood between Forsmark in Östhammar Municipality and Laxemar in Oskarshamn Municipality.

The siting process was based on two fundamental requirements: There must be bedrock that permits long-term safe disposal, and there must be political and popular support in the concerned municipality¹.

The geological limit values which SKB has established are at such a level that Swedish bedrock at a depth of 500 metres generally meets the requirements. But the fact that the siting process has the backing of the municipal inhabitants in Östhammar and Oskarshamn has permitted detailed geological investigations, which has in turn yielded geological knowledge of these areas that is lacking in other parts of the country.

This chapter presents the Council's assessment of SKB's reported findings concerning the geological premises for SKB's site selection.

2.1 Geological background in Forsmark and Laxemar

The final site selection has been determined by how geological conditions make it possible in practice to achieve the long-term safety level defined in the Swedish Radiation Safety Authority's regulations.

The bedrocks in the two investigation areas are to some extent related. They were formed during different phases of the Sveco-

¹ Final repository for spent nuclear fuel in Forsmark – basis of decision and reasons for site selection. SKB 4 June 2009. <http://www.skb.se/f0a51b8e-d851-492c-a218-32bd7a857b1b.fodoc>

fennian, or Svecokarelian, orogeny (process of mountain formation). The bedrock in Forsmark is slightly older (1.9 billion years) and was metamorphosed (deformed and altered) during this orogeny. The slightly younger bedrock in Laxemar is 1.8 billion years old and was formed under somewhat different conditions, after the metamorphosis that affected the Forsmark area. Traditionally, the bedrock in Laxemar has been assigned to the Trans-Scandinavian Igneous Belt, which extends straight across Sweden and Norway, from Småland in the southeast to Lofoten in the northwest.

In order to obtain greater reliability in the three-dimensional modelling of the bedrock in the two areas, SKB has carried out both core drilling and percussion drilling², as well as different types of geophysical surveys.

² Core drilling yields integral drill cores, which are studied in detail. Percussion drilling yields fragmented rock material, which is examined by means of different geophysical methods.

Figure 2.1



Measurement of drill cores from test drilling. Photo: Carl-Robert Lindqvist. Source: SKB.

2.1.1 The bedrock in the Forsmark area

The candidate area in Forsmark is approximately 6x2 kilometres in size and consists of a tectonic lens, which is a relatively unaffected and protected rock volume surrounded by thick shear zones³. The lens is oriented in a northwesterly-southeasterly direction and is most thoroughly investigated in the northwestern portion, where the final repository is planned to be located. In addition to detailed characterization of the geology at the ground surface, 23 cored boreholes have been drilled in this limited area, 22 of which are drilled to repository depth or more. An additional two cored boreholes have been drilled outside the actual candidate area. The integral drill cores have been studied in detail. In addition to these direct investigations of the geology of the area, some 40 percussion boreholes have been drilled and different kinds of geophysical surveys have been carried out in order to obtain a higher resolution, three-dimensional model of the bedrock.

The dominant rock type in the area, down to at least 1,000 metres depth, is a metagranite (metamorphic granite). Secondary rocks include aplitic metagranite, amphibolite, granodiorite-tonalite, pegmatite and pegmatitic granite. Other rock types comprise only a few percent and consist of felsic to intermediate volcanic rocks, skarn, basic and ultrabasic rocks plus diorite and quartz diorite, all of which are more or less metamorphosed (see Infobox 1).

The dominant metagranite has a relatively high quartz content (20–35 %), which permits good thermal conductivity⁴. This rock type also has good strength, i.e. it can withstand high stresses without fracturing.

Structures in the bedrock

The Forsmark lens is bounded by the Singö Zone in the east and by the Eckardfjärden Zone and the Forsmark Zone (deformation zones) in the west.

A subhorizontal complex deformation zone, or rather a seismic reflector, indirectly observed by geophysical surveys, runs at depth, southwest of the repository area in Forsmark⁵. The zone is

³ A shear zone is a bedrock area characterized by intensive deformation.

⁴ SKB, 2008a.

⁵ Juhlin & Stephens, 2006.

assumed to reach the ground surface a kilometre or so north of the investigation area, but new investigations indicate that it probably constitutes a blind structure⁶, i.e. it does not intersect the ground surface. The reflector has a southerly dip, and beneath the repository area the structure is larger than 1,000 metres. There are different possible interpretations of what the seismic reflector represents. Juhlin & Stephens have suggested banded amphibolites⁷, but it could possibly constitute a water-bearing brittle zone⁸. The presence of water-bearing zones lowers the quality of the rock as an external barrier.

The limited number of seismic profiles – along with the identification of (probably) blind, non-characterized structures – means that there is a lack of knowledge in existing three-dimensional models of the area. In order to obtain a more reliable picture of the bedrock, a dense network of seismic profiles must be carried out and any reflectors must be characterized geologically and hydrologically.

Fractures and water flow rate

Down to a depth of 200 metres, the candidate area in Forsmark is the relatively commonly occurring type with gently-dipping water-bearing fractures that are hydraulically connected with each other over large areas. Together with subhorizontal brittle deformation zones, these are the principal water flow pathways and form a network of water-bearing fractures. The frequency of water-bearing fractures declines markedly with depth, and at 400 metres depth the distance between them is more than 100 metres, which means that there is little chance for water to be transported.

The hydrogeological fracture model consists of six domains, where the extent of water-bearing fractures has been extrapolated. This extrapolation means that there is an uncertainty in the interpretations of the areas that lie between the observations and thereby in the hydrological models.

Reflectors from a denser network of seismic profiles could indicate the presence of more water-bearing fractures, which would affect the hydrological model.

⁶ Juhlin, personal communication, 2010.

⁷ Juhlin & Stephens, 2006.

⁸ Juhlin, personal communication, 2010.

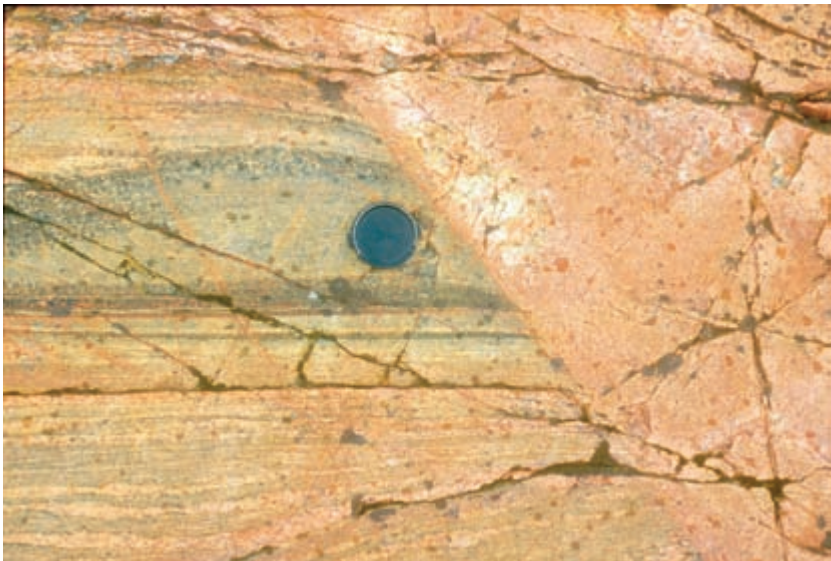
Rock stresses

The rock stresses in the Forsmark area are higher than normal for Swedish bedrock, but they do not increase appreciably with depth. At 500 metres depth, the horizontal rock stresses are on average 41 megapascal (MPa). In combination with the temperature increase generated by the radioactive waste, the relatively high rock stress can cause spalling (i.e. breakout) in the deposition tunnels and holes.

The groundwater

Both the salinity and the age of the groundwater in Forsmark increases with depth. The bedrock at repository depth has probably been isolated from the input of water from levels nearer the surface for a very long time. In the subhorizontal water-bearing brittle zone southeast of the candidate area, there are, however, traces of water that probably stems from the Littorina Sea, which covered the area between 9,500 and 5,000 years ago.

Figure 2.2



Gneiss. Photo: Karin Högdahl.

Figure 2.3



Granite. Photo: Karin Högdahl.

2.1.2 The bedrock in the Laxemar area

A total of 46 core boreholes have been drilled for the site investigation in the Laxemar area, 19 of which are drilled down to repository depth or more, and 17 of these are in the priority area. In addition, 43 percussion boreholes have been drilled. In comparison with Forsmark, the bedrock in Laxemar is relatively well preserved, i.e. not metamorphosed, and is dominated by Ävrö quartz monzodiorite and Ävrö granite. Other rock types are other types of granite and quartz monzodiorite, pegmatite, diorite and gabbro, and dolerite. The Ävrö quartz monzodiorite and Ävrö granite are both relatively quartz-poor (15–20 %) and thereby have relatively low thermal conductivity⁹. Since radioactive waste generates heat, a repository in bedrock with high thermal conductivity is desirable. The strength of the rock varies. The priority area is bounded by steeply dipping, northeasterly-southwesterly swaths of deformation zones.

⁹ SKB, 2009.

Structures in the bedrock

Even though the bedrock in the Laxemar area is relatively well preserved, there is a local, weak, gently dipping foliation, i.e. a planar structure caused by parallel arrangement of the minerals in the rock. Foliation generally has a negative effect on the strength of the bedrock. There are shear zones in the southern part of the area, which form at high temperatures. They are located in different types of hypabyssal rocks. Ductile (formed at high temperatures under ductile deformation) to semi-brittle shear zones are generally occurring. Many of these zones have also been affected by deformation in connection with subsequent geological events, under brittle conditions when the temperature of the bedrock was lower. Different generations of mineral-sealed fractures have been documented; The youngest are related to the Caledonian orogeny about 0.5 billion years ago¹⁰.

The frequency of open fractures between the bordering shear zones in the investigation area is low, but down to 150 metres there are plenty of water-bearing fractures. They are less common at greater depth. Down to 150 metres the average distance between the fractures is about 1 metre, and between 400 and 650 metres the average distance increases to between 5 and 10 metres. At 700 metres the fracture distance is estimated at more than 100 metres, but due to the limited number of observations this estimate is uncertain and the depth to drier rock could be greater. The salinity and age of the groundwater increase with depth, and the rock stresses are considered to be comparable with those in the Äspö HRL and normal for Swedish bedrock. No large gently dipping deformation zones or large fractures have been identified in the area. Fractures and deformation zones increase the permeability of the bedrock, and intersecting systems can form potential water-bearing networks.

The groundwater

As in Forsmark, both the salinity and the age of the groundwater increase with depth. A mixture of marine, glacial, deglacial and meteoric water (water from different types of precipitation) occurs at progressively shallower levels. Parts of the bedrock in Laxemar

¹⁰ SKB, 2008b.

lay above the Littorina Sea's highest coastline and therefore lack marine water from this time.

Infobox 2.1

The bedrock is composed of rock types that are defined on the basis of their mineral composition and manner of formation. There are three main rock types: igneous, sedimentary and metamorphic. Igneous rocks have solidified after being molten, which means they have either crystallized at depth or solidified on the surface as products of a volcanic eruption. Sedimentary rock types are either clastic (formed from weathering products), chemically precipitated or formed from organic matter. Metamorphic rock types have been altered under elevated pressures and temperatures. Before their transformation, metamorphic rocks may have been igneous or sedimentary or may have undergone metamorphosis previously. Metamorphic rock types are often deformed.

Rock mechanical properties and hydrogeological conditions are largely determined by the composition and structure of the bedrock, which also affects the composition of the groundwater and the rock's ability to retard solute transport.

Rock types

Amphibolite: Metamorphosed *basic rock*.

Aplite: Fine-grained, light igneous hypabyssal rock with the same composition as *granite*.

Basic rocks: Igneous rocks with a SiO_2 content of between 45 % and 54 %, e.g. *gabbro* and *dolerite*. They are often rich in dark minerals.

Dolerite: Basic, igneous rock that occurs as dykes. Crystallized at shallow to medium-great depths.

Diorite: Igneous plutonic rock with intermediate SiO_2 content (52–63 %).

Felsic to intermediate volcanic rocks: Light, quartz- and feldspar-rich volcanic rocks.

Gabbro: Basic igneous plutonic rock.

Granite: Igneous plutonic rock with high SiO_2 content ($> 63\%$) that consists of quartz, feldspar and mica or amphibole.

Granodiorite-tonalite: Igneous plutonic rocks that have a higher content of dark minerals than granite, and as a rule a lower content of these minerals than basic rocks. Tonalite has a lower quartz content than granite.

Quartz diorite: Igneous plutonic rock with a higher content of quartz than *diorite*. Also called tonalite.

Quartz monzodiorite: Relatively calcium-rich igneous plutonic rock with an intermediate Si_2 content (52–63 %).

Pegmatite: Coarse-grained, light igneous plutonic rock that often occurs as dykes.

Pegmatic granite: Coarse-grained, often heterogenous granite.

Skarn: Ca-Mg-silicate-rich metamorphic rock.

Ultrabasic rocks: SiO_2 -poor ($> 45\%$) igneous rocks that are rich in dark minerals.

2.2 Earthquakes

2.2.1 Observed earthquakes

Earthquakes occur when energy is quickly or suddenly released by movements along planes of movement, called faults, initiating seismic waves. Earthquakes are a common phenomenon, and small earthquakes occur in Sweden every day. Perceptible earthquakes are uncommon in Sweden, however. Earthquakes with a magnitude of 4 to 5 on the Richter scale occur most commonly along the coast of Norrland, in southwestern Sweden and along geological planes of weakness (lineaments) in the northern part of the country. More powerful earthquakes (with a magnitude of 6 or more) have not been observed in recorded history. During the period 1904 to 2005, earthquakes with a magnitude of more than 3 have been very unusual in both Laxemar and Forsmark.

Recorded earthquakes in Sweden occur at depths of between 7 and 35 kilometres. In the southern part of the country, the focus of earthquakes lies at a depth of less than 18 kilometres, and in the north they are shallower than 13 kilometres. The seismic movements mainly take place along older, already existing fractures and

faults. At depths greater than 35 kilometres, the Earth's crust is seismically inactive in Sweden.

The relatively powerful earthquakes in northern Sweden are related to movements along late-glacial to post-glacial faults¹¹. But the principal seismic activity took place several thousand years ago. It is unclear whether the seismic activity has ceased or whether major movements will take place along these planes of movement¹².

The seismic activity along the coast of Norrland occurs where postglacial land uplift is greatest (it is between 7 and 9 millimetres per year). This activity coincides with the contour line for the thickness of the Earth's crust, which shows that this thickness decreases from its maximum in central Finland and the Bay of Bothnia. The earthquake concentration in southwestern Sweden also coincides with the declining thickness of the Earth's crust, and similar relationships between seismic activity and decreasing crustal thickness have previously been noted elsewhere as well¹³.

Geodetic data from stationary GPS stations at different places in Sweden, Finland and Norway show that the maximum vertical movement is 11 millimetres per year and the maximum horizontal movement is 2 millimetres per year¹⁴. These movements are caused by the readjustment of the Earth's crust after the latest ice sheet retreated and melted. In order to evaluate superficial rock movements caused by other phenomena, such as plate tectonic processes (see Infobox 2), the local GIA values must be taken into account and compensated for. (GIA stands for *Glacial Isostatic Adjustment*).

Rock movements in the superficial parts of the Earth's crust can cause brittle fractures in the bedrock and have an adverse effect on a final repository. Active rock movements have been indicated at different places in Sweden, including the Laxemar-Simpevarp area, but certainty is lacking in both the results and the interpretations¹⁵. A limited number of GPS data measured on different sides of a fault zone in the Laxemar-Simpevarp area show a statistically significant variation indicating that the northern side has moved relatively towards the east at a rate of 1 millimetre per year¹⁶. This movement has not been accompanied by seismic activity, but could

¹¹ Bödvarsson et al., 2006.

¹² SKB, 2008b.

¹³ Kinck et al., 1993.

¹⁴ Johansson et al., 2002.

¹⁵ Pan et al., 1999; Sjöberg et al., 2004; Bödvarsson et al., 2006.

¹⁶ Sjöberg et al., 2004.

nevertheless be related to tectonic activity at depth¹⁷. However, it must be pointed out that the results are very uncertain, since the indicated movement at the surface is of the same magnitude as the margin of error in the measurement method, and most of the data are not statistically significant¹⁸.

Infobox 2.2

The Earth's crust consists of a number of plates that move in relation to each other in what are known as plate tectonic processes. Some plates collide while others drift apart or alongside each other. The boundary between the North American plate and the Eurasian plate, to which Sweden belongs, is in the middle of the Atlantic. These plates are drifting apart at a rate of about 2 centimetres per year, which causes a buildup of stresses in the bedrock. When these stresses are released, earthquakes and seismic activity occur.

2.2.2 Prehistoric earthquakes – late- to post-glacial earthquakes

Signs of prehistoric earthquakes (palaeoseismic activity) in Sweden manifest themselves either directly as displacements of the interface between the bedrock and the overlying soil layer, or indirectly in seismically deformed Quaternary deposits (Infobox 3).

Palaeoseismic activity in Sweden has been explained as being due to a combination of plate tectonic processes in the Atlantic (see Infobox 2) and the release of accumulated rock stresses caused by the rapid retreat of the ice sheet. Accumulated horizontal stress may also have been created by the depression of the bedrock caused by the thick ice cover.

In northern Sweden, a number of major fault planes in the bedrock have been identified along major zones of weakness (lineaments), and it is likely that they were formed by powerful earthquakes (with a magnitude of 8 on the Richter scale)¹⁹. According to SKB, there is no certain proof that similar late- or post-glacial

¹⁷ Bódvarsson et al., 2006.

¹⁸ SKB, 2008b.

¹⁹ Lagerbäck & Sundh, 2008.

faults have occurred in southern Sweden²⁰. This has, however, been questioned²¹.

In the vicinity of the Laxemar-Simpevarp area and in Forsmark, linear patterns and elevation differences, known as morphological lineaments, occur in the landscape where deformed Quaternary deposits have been encountered. However, they cannot be attributed to palaeoseismic activity with certainty²².

Disturbed Quaternary deposits have been encountered in different parts of Uppland, but they are generally limited in area and very local, which suggests that they have not been caused by powerful earthquakes²³. The disturbance-prone Quaternary deposits in the Forsmark area are undeformed. The fact that these deposits are undisturbed indicates that the area has not been subjected to any appreciable seismic activity since the sediments were deposited. In the Uppsala Esker, however, dewatering structures and slump folds have been found, which are considered to be caused by local hydrological conditions rather than by seismic activity²⁴. The possibility of other interpretations cannot be ruled out, however.

Large, disturbance-prone Quaternary deposits have been encountered in the Oskarshamn area as well²⁵. They also occur in the upper parts of sediments considered to derive from earlier ice ages. Similar Quaternary deposits at lower levels are undeformed, however, which indicates that the area has not been affected by large earthquakes. However, it is important to point out that the investigated deposits were raised above the sea level of that time relatively soon after they were deposited and were thereby dried out and compacted, making them less disturbance-prone. They are therefore uncertain seismic markers.

2.3 Points of departure for site selection

The selection of a site for the final repository for spent nuclear fuel should be made with a view to its purpose and in compliance with the requirements of the Nuclear Activities Act, the Radiation Protection Act and the Environmental Code. The purpose is to achieve

²⁰ 2008b.

²¹ t.ex. Mörner et al., 2008, and references therein.

²² Lagerbäck et al., 2006; Lagerbäck & Sundh, 2008.

²³ Lagerbäck & Sundh, 2008.

²⁴ Lagerbäck et al., 2005.

²⁵ Lagerbäck et al., 2006.

long-term safe disposal with reasonable consequences for the surrounding area and the environment. Two areas, Forsmark and Laxemar, have been thoroughly investigated, and according to SKB the choice should fall on the area with the best conditions and the least chance of intrusion and disturbance.

2.3.1 Comparison between the areas in terms of composition and structure of the bedrock

Knowledge of the composition of the bedrock is good in both Forsmark and Laxemar. However, the three-dimensional extent of the underrepresented rock types (see Infobox 1) is less well known due to the relatively limited number of drill cores. Since these rock types can affect the quality of the bedrock, they should be continuously modelled mathematically during the construction phase in Forsmark.

The bedrock in the Forsmark candidate area has a higher quartz content than that in Laxemar, which means that the thermal conductivity of the bedrock is higher and the deposition area can therefore be made smaller in Forsmark than in Laxemar.

The degree of alteration of the bedrock, i.e. recrystallization of existing minerals or formation of new ones, can significantly affect its chemical and physical properties, which SKB has also tried to assess in its site investigations. No estimates of the degree of alteration of the bedrock have been reported for Forsmark, but most of the rocks here are altered, while a smaller portion of the bedrock in Laxemar is altered. A more recently altered, vuggy granite has been encountered in one of the drill cores in the Forsmark deposition area. The vugs were formed by selective precipitation of quartz and coincide with heavy oxidation. This alteration affects both the chemical and physical properties of the rock and leads to increased porosity and permeability and reduced resistivity and strength. SKB therefore needs to determine the extent of the porous granite in further investigations in Forsmark, and investigate whether, and if so how, this and other alterations affect the geochemistry, transport properties, strength and thermal conductivity of the rocks.

Good knowledge exists of the large-scale structural evolution of both Forsmark and Laxemar, but on a detailed scale both major and minor deformation zones and other structural elements are

directly linked to the spatial distribution of the number of boreholes. In this respect, the location of the boreholes in Forsmark is better than in Laxemar, which means that there is greater uncertainty in Laxemar regarding the occurrence and extent of major and minor deformation zones and other structural elements²⁶.

2.3.2 Ore deposits

Felsic and intermediate metavolcanic rocks are common in north-eastern Uppland, outside the candidate area, and ore is frequently found in these rock types. Iron ore was mined in Dannemora, about 25 kilometres southwest of Forsmark, up until 1992, and there are plans to resume production in the near future. Traces of mining and attempted mining in the form of old mine holes and pits are common in the area. Traces of mining also occur in volcanic rocks just outside the candidate area, and a number of exploration permits for copper exist in the zone.

Felsic to intermediate metavolcanic rocks can be found north-east of the candidate area as well. Aside from a number of small islands, these rocks are largely covered by water and have therefore not been examined more closely. The possibility can therefore not be ruled out that these rocks contain non-magnetic mineralizations, for example of hematite or sulphide, that are not registered by magnetic surveys. Furthermore, the bedrock in the north-western part of the tectonic lens in Forsmark, just outside the priority area, is heavier than average. Heavy rock types may consist of gabbro or the like, or of different types of mineralizations. The occurrence of these rock types, even when they are not exposed, is indicated by gravimetric surveys, where they constitute a positive geophysical anomaly. It should be pointed out that the repository in itself will constitute a strong positive geophysical anomaly, owing to its mass and the presence of iron. This means that there is some risk that the area will be subjected to ore prospecting in the distant future²⁷.

Prospecting with the aid of geophysical methods for deep-lying ore bodies that do not reach the ground surface will probably become increasingly common. Until the metavolcanic rocks north-east of the candidate area have been investigated, the possibility

²⁶ Toverud, 2010.

²⁷ Toverud, 2010.

that future exploitable mineral deposits exist in the Forsmark area should not be ruled out.

This problem does not exist in the Laxemar area²⁸.

2.3.3 Probability of earthquakes

The probability of major earthquakes in both Forsmark and Laxemar is very small, but not negligible.

2.3.4 Rock stresses

Interpreted rock stresses in Forsmark are much higher than in Laxemar, which could mean that extensive reinforcement work must be undertaken during the construction phase in Forsmark.

Infobox 2.3

Quaternary refers to the geological period extending about 2 million years into the past. Sweden's surface deposits were mainly formed during this period by glacial processes associated with the continental ice sheets. Quaternary deposits consist mainly of minerals and rock fragments. Quaternary deposits deposited by the ice (till) are generally unsorted, while alluvial deposits have a more limited grain size variation. Coarse-grained Quaternary deposits are often non-cohesive soils whose shear strength consists mainly of friction. In fine-grained deposits, the contact surface between the constituent particles is large and the cohesive force is high, so they are not disturbance-prone. Loosely packed and water-saturated non-cohesive soils are, however, disturbance-prone and can behave like a liquid when they are subjected to shaking from e.g. an earthquake. They are generally good palaeoseismic markers.

²⁸ (Lindroos, 2004).

2.4 Conclusions of the Swedish National Council for Nuclear Waste

The geological conditions in Forsmark constituted part of the premises for SKB's site selection. The final alternatives were also identified on the basis of democratic principles, inasmuch as the site selection process has only included municipalities that have voluntarily participated in the process. The Council believes that voluntary participation is an important principle in the site selection process. At the same time, the Council notes that the detailed geological knowledge that now exists of these areas is unmatched in other parts of the country.

Comparison of the state of knowledge regarding the geology in the site selection areas

In view of the geological knowledge SKB has presented for site selection, the Council can conclude that good knowledge concerning the composition and large-scale structural evolution of the bedrock exists both in Forsmark and in Laxemar. However, less detailed knowledge exists concerning both major and minor deformation zones and other structural elements that can affect the quality of the repository. This knowledge is directly linked to the spatial distribution of the number of boreholes, which means that there is greater uncertainty regarding deformation zones in Laxemar.

There is also a certain lack of knowledge in the hydrological models. In order to reduce the uncertainty in the models for Forsmark, it is recommended that a denser network of seismic profiles be carried out.

Knowledge of the three-dimensional extent of the underrepresented rock types is also deficient, and the same applies to the observed altered and vuggy granite in Forsmark. These rock types can affect the capacity of the bedrock as an external barrier and should be modelled continuously during the construction phase. Furthermore, the bedrock east of the investigation area in Forsmark is potentially ore-bearing and should be more thoroughly investigated. The occurrence of ores in the vicinity of Forsmark could entail a long-term safety risk (risk of intrusion). This problem does not exist in the Laxemar area.

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3 Durability of the barriers in the final repository environment

The engineered barriers (copper canister and bentonite buffer) are important guarantors of the long-term safety of the final repository for high-level spent nuclear fuel. Recently, however, new research results have challenged existing knowledge concerning the properties of both the copper canister and the bentonite buffer and called their long-term function into question.

In last year's state-of-the-art report, the Council described the background and issues associated with research results on corrosion of copper in water and erosion of bentonite in buffer and backfill¹. The Council urged SKB to continue its research on the properties of copper in different environments where the metal comes into contact with water. In the spring of 2010, a report was published from the Council's seminar on copper corrosion, which was held in November 2009.² In this year's state-of-the-art report, the Council recounts what has happened in this respect during 2010 and offers further viewpoints on the research that is being conducted. Some of the viewpoints are the result of a meeting with a number of corrosion experts at the Massachusetts Institute of Technology, MIT, in November 2010.

The Council's Nuclear Waste State-of-the-Art Report 2010 also contained descriptions of some of the challenges to the bentonite buffer and the backfill that have been posed recently. This applies in particular to bentonite erosion in the repository and the backfill, which is perceived as a threat, particularly under postglacial conditions. Another topical issue is the process of water saturation of

¹ Nuclear Waste State-of-the-Art Report 2010 – challenges for the final repository programme. SOU 2010:6.

² Mechanisms of Copper Corrosion in Aqueous Environments. A report from the Swedish National Council for Nuclear Waste's scientific workshop, on November 16, 2009. Report 2009:4.

the bentonite, which can affect the properties of the bentonite in the short and long term. The latter issue is examined more closely in this year's state-of-the-art report, which also contains viewpoints on the new research presented by SKB during 2010.

3.1 On corrosion of copper in contact with water

The copper canister is an important barrier in the KBS-3 method, since it is expected to be completely watertight and corrosion-resistant. It is therefore necessary to have well substantiated data on copper corrosion in the final repository environment in order to uphold the credibility of the KBS-3 method. Complete knowledge is needed on mechanisms, rates and driving forces for copper corrosion under the conditions that prevail in the final repository. In 2009, a group of researchers from KTH published results that challenged current knowledge on copper corrosion under oxygen-free (anoxic) conditions, which are expected to prevail in the final repository³. Their experimental results indicate that copper can corrode spontaneously even in pure water, whereby hydroxide ions (OH^-) are taken from the water and hydrogen gas (H_2) is evolved. This means that general corrosion of copper could eventually occur in the final repository.

However, their results have been the subject of several critical reviews and challenges, mainly because they conflict with known thermodynamic data on how copper reacts in pure oxygen-free water⁴.

In November 2009, the Swedish National Council for Nuclear Waste arranged an international scientific seminar entitled "Mechanisms of Copper Corrosion in Aqueous Environments," which was attended by nearly 300 persons. Invited experts from different countries objected to the suggestion that the new research results were unambiguous, but admitted they might possibly occur under extreme conditions in ultrapure water. Even if copper could actually react in ultrapure water in the manner suggested by these researchers, it could not cause any serious attacks on the copper canister during its life of over 100,000 years in the final repository. This conclusion has been based on the data on

³ Hultquist et al. 2007, 2009.

⁴ e.g. Apter et al., 2009; King, 2009.

hydrogen gas evolution presented in the published experimental results by Hultquist *et al.*

Based solely on the laws of thermodynamic, corrosion of copper in oxygen-free water is only possible if the hydrogen pressure is extremely low⁵ and the concentration of copper(I) ions (Cu^+) is furthermore negligible. It is the partial pressure of hydrogen (p_{H_2}) and the concentration of copper ions and hydrogen ions (H^+) that constitute key variables in the process of copper corrosion in water, and thermodynamic calculations show that these parameters must have very low values in order for copper to corrode. Copper is thus very resistant to corrosion in oxygen-free water, but this can be drastically affected in the presence of sulphide ions and some other undesirable impurities.

3.1.1 Thermodynamic calculations

Thermodynamic calculations performed by Professor Digby Macdonald⁶ show that the results of Hultquist *et al.* do not necessarily conflict with the laws of thermodynamics, provided that the experiments were performed under the extreme conditions described above or if the water contained impurities such as sulphide ions. If the basic conditions for corrosion are met, the process will be initiated, causing the hydrogen pressure to increase and the concentration of copper(I) ions to rise until the values exceed the equilibrium values in a system with limited mass transport. At equilibrium, the corrosion rate is determined by the transport of reactants to the metal surface and the transport of the reaction products away from the corrosion site.

The sometimes contradictory results obtained in studies of copper corrosion in oxygen-free water, where some experiments show that copper corrodes while others show the opposite, can probably be explained by varying initial conditions in the experiments, for example the purity and structure of the copper metal and the purity of the water.

⁵ $p_{\text{H}_2} < 10^{-11}$ atm at 25°C.

⁶ Pennsylvania State University, USA.

3.1.2 The experts' conclusions

The statements of the international experts say in summary that the newly published results, which show that copper can corrode in oxygen-free water at room temperature, are controversial and challenge current knowledge regarding thermodynamic data applicable to the combination of copper and water (Cu/H₂O). Pure water cannot normally oxidize copper, nor can water containing low concentrations of chloride ions. As described above, copper can only be attacked temporarily under extraordinary conditions, and the new experimental results regarding copper corrosion in pure oxygen-free water can therefore not be applied to the expected conditions in the final repository and cannot be used to predict the long-term behaviour of the copper canister.

Other researchers have not succeeded in replicating the results of the experiments performed by Hultquist *et al.* The big increase in hydrogen pressure during the experiment may indicate that all variables were not completely under control. The experimental procedure may contain sources of error not yet identified. The experts said that it is therefore necessary for a third party to replicate the experiments with a methodology and apparatus as similar as possible to those used by Hultquist *et al.*

3.1.3 The copper canister in the final repository

The evolution of the geochemical conditions expected to prevail in the final repository is thoroughly evaluated and described⁷. Oxygen from the atmosphere will be present in the final repository when it is closed (in water and bentonite), and the decay heat from the canister will create humid and oxidizing conditions. The oxygen is expected to be consumed relatively rapidly (in a couple of hundred years) through a number of processes including copper corrosion and reactions with microbes and other impurities in the buffer and the backfill. The electrochemical environment near the copper canister will eventually change from warm and oxidizing to cold and reducing when the oxygen has been consumed and the decay heat from the canister declines. Before the bentonite buffer has been water-saturated, SKB figures on a general corrosion depth of 30 thousandths of a millimetre (30 μm) and a maximum corrosion

⁷ King et al., 2002.

depth of and $300\ \mu\text{m}$, based on the quantity of oxygen expected to be available at closure⁸. Under oxygen-free conditions (which will exist for an estimated 99.9 % of the time), the corrosion is expected to slow down and eventually cease, since the hydrogen pressure increases along with the concentration of copper ions in the vicinity of the canister.

Infobox 3.1

The groundwater in the repository is far from pure, common impurities being chlorides (Cl^-), carbonates (HCO_3^-), sulphate (HSO_4^-) and sulphide ions (HS^-). Sulphide activates copper by forming precipitates of copper sulphide (Cu_2S) at electrochemical potentials that are much more negative than necessary for the formation of copper oxide (Cu_2O). This means that copper can corrode under oxygen-free conditions, and calculations show that it is highly likely that copper corrodes in the presence of sulphides. Since even relatively small quantities of sulphide ions in the final repository can result in corrosion of copper, transport of sulphide ions to the canister must be prevented by engineering measures. In the presence of sulphide, copper is activated and will corrode by forming stable and poorly soluble compounds of copper sulphide (Cu_2S).

3.1.4 The corrosion process is complex

The corrosion process contains both electrochemical and complex chemical components. Electrochemical reactions entail an exchange of electrons between the copper metal and one or more reactants in the surroundings, for example oxygen or hydrogen ions in the water. The complex chemistry is affected by the quantity and type of impurities and entails that resultant copper ions are precipitated as copper oxide or, in the presence of sulphide ions, as copper sulphide, and copper ions can also be complexed by chlorides and carbonate ions in the water. These reactions interact and constitute driving forces for the corrosion process in certain environments.

⁸ King et al., 2002.

Studies of copper corrosion can therefore not be limited to pure, oxygen-free water. As described in the above infobox, certain types of impurities must be prevented from coming into direct contact with the copper canister for a long time. An important factor in this context is the properties of the bentonite buffer, which are dealt with in the next section. One could say that the long-term function of the copper canister is dependent on the effective function of the buffer, which means that the copper canister is not a completely independent barrier.

If the copper canister is in direct contact with groundwater containing numerous corrosive substances for a long time, the canister will corrode. Long-term safety is thus dependent on the ability of the bentonite to protect the canister from a flow of groundwater⁹.

This has been demonstrated by, among others, Professor Digby Macdonald at the above-mentioned symposium on copper corrosion in Stockholm in 2009. The scope of the corrosion depends on the quantity of sulphides and their diffusion through the bentonite buffer to the copper canister. The resultant copper sulphide does not protect the surface from further corrosion, which means that sulphides and other sulphur-containing compounds (such as polysulphides and different types of sulphates) pose long-term threats to the copper canisters and should be studied thoroughly. Potential sulphur sources include pyrite (FeS_2) and sulphates in the bentonite. Sulphate-reducing bacteria can transform sulphates to sulphides in the final repository.

3.1.5 Requirements on openness and quality

SKB's research programme on the properties of the copper canister as a barrier in the repository is being followed with great interest by many individuals as well as organizations and regulatory authorities. The research must of course be of high scientific quality, where the results are evaluated objectively on the basis of clearly formulated reasons and hypotheses. Even though the research is conducted by

⁹ It should be emphasized that the Swedish Radiation Safety Authority, in its regulations and general recommendations (SSMFS 2008:21), Section 7, prescribes that "the barrier system shall comprise several barriers so that, as far as possible, the necessary safety is maintained in spite of a single deficiency in a barrier". In view of the fact that there are deficiencies in the bentonite buffer that can lead to corrosion of the copper canister, it is justified to ask the question whether this requirement is satisfied in the current design of the KBS-3 system.

different outside consultant groups and university departments, SKB must take responsibility for the reporting of results and conclusions with observance of good research ethics.

When it comes to the issue of copper corrosion in different environments, one sometimes gets the impression that the research projects have been aimed at confirming already held beliefs, rather than seeking new knowledge. This does not mean that the quality of the research is poor, but when the results are not as expected the principle should be to report the new findings openly. It is unnecessary for SKB to expose itself to outside criticism and suspicion on the part of media, regulatory authorities and the environmental movement when credibility is more important than ever now that an application is to be submitted¹⁰. The Swedish National Council for Nuclear Waste hopes that SKB will continue its research in the area of copper corrosion with great openness, by engaging independent research groups.

3.1.6 The research continues

SKB's continued research programme with respect to copper corrosion includes modelling and experimental studies both in the laboratory and under more repository-like conditions. The research is aimed at investigating whether the copper canister has good enough properties with respect to corrosion and strength in the final repository. The planning of the research programme has been described in RD&D Programme 2010 and includes the following subareas:

- Copper corrosion and stress corrosion cracking in the sulphide/water system
- Copper corrosion in compacted bentonite
- Copper corrosion in repository-like environments (LOT and Minican)
- Copper corrosion in oxygen-free water
- Independent experiments to replicate the results of Hultquist et al.

¹⁰ SSM; Research 2010:17; Ny Teknik 1 Dec. 2010.

The studies of copper corrosion under repository-like conditions are aimed at avoiding the problems associated with the interpretation of the results of more short-duration and limited laboratory experiments. It is important to obtain knowledge concerning the evolution of the environment in compacted bentonite and how this affects the corrosion rate. It is naturally of interest to identify possible local corrosion (“pitting”) and the role of the corrosion products in continued general corrosion of the canister.

Creep in the copper metal causing deformation and possible failure of the canister due e.g. to uneven swelling of the bentonite can be another long-term threat in the final repository. The influence of creep on the properties of the copper canister in the long term is an important area for further research.

In the project “Miniature canister corrosion experiment,” the experiments have been designed to understand the corrosion of the cast iron insert in the canister if the canister is damaged so that water can penetrate. During the experiment the canister’s corrosion potential and the redox potential in the environs¹¹ will be registered and the composition of the penetrating water and the hydrogen pressure in the canister will be measured along with how this affects the strain on the outside of the canister. The cast iron is expected to corrode by means of e.g. galvanic corrosion and form products such as magnetite, while hydrogen gas is evolved. The experiments will be performed at a temperature of about 15°C and will proceed for at least 5 years before the canisters are retrieved for examination.

3.2 On bentonite as a barrier in wet and dry conditions

The discussion of the long-term properties of the copper canister as a watertight barrier in the final repository has focused attention on the importance of the bentonite’s role as a buffer. Although copper is a relatively corrosion-resistant material, as described above the canister is not immune in the environment expected to exist in the repository entailing contact with the groundwater.

The function of the copper canister as a watertight barrier is highly dependent on the ability of the bentonite buffer to protect

¹¹ The redox potential indicates whether the environment is oxidic or anoxic, i.e. whether oxygen is available in the environment or not.

the canister from corrosive substances in the groundwater. The groundwater contains a number of substances (ions and microbes) that constitute potential threats to the canister. It is no exaggeration to say that freely flowing groundwater in contact with the canister could lead to devastating consequences in the long term, even under oxygen-free conditions. The long- and short-term properties of the bentonite buffer are thereby crucial for the performance of the repository, and it is therefore important to summarize the knowledge that exists concerning the properties of the bentonite in different environments.

There are thousands of published technical reports and scientific articles concerning bentonite and its use in various engineering contexts. The most important applications are as a binder in foundry sand, in the pelletizing of iron ore, in drilling fluids for oil drilling, for sealing in the construction industry, and for absorption of flammable liquids and other liquids (for example in cat litter), oils and greases in the food industry. Against this background it is easy to understand that knowledge of the general properties of the bentonite is very broad and to some extent also deep.

The ambition here is not to give a complete account of the aggregate body of knowledge regarding bentonite, but to concentrate on a few parameters critical for the final repository.

3.2.1 Specific requirements in the final repository

Very specific requirements must be made on the type of bentonite that will be used in the final repository, mainly with regard to its total content of minerals that swell in water, but also with regard to limitation of impurities that can affect the copper canister in the long term, such as sulphides and other sulphur-containing compounds. Furthermore, the bentonite should contain an optimal composition of minerals and ions, since commonly occurring minerals (such as quartz, feldspars, calcite, gypsum, pyrite and siderite) have different properties with respect to solubility in water, hardness, particle size distribution etc. In previous statements, the Swedish National Council for Nuclear Waste has emphasized how important it is that SKB give a clearer account of how the composition of the bentonite affects the properties of the buffer in the long and short term¹².

¹² See e.g. SOU 2008:70.

The properties that can be expected to vary with the composition of the bentonite are, for example, swelling in water, erosion, cementation, mechanical properties, filtration of solutes and colloids, pH and ionic strength of the pore water, living conditions for microorganisms, thermal conductivity and chemical and physical stability. Most of the above properties are directly or indirectly dependent on the concentration of montmorillonite in the bentonite, but other minerals and impurities also affect the properties to a varying extent. Other important factors for optimizing the properties of the buffer are created by the pretreatment to which the bentonite is subjected before it is placed in the repository. This includes grinding, addition of additives and compaction, all of which affect the properties in different ways.

3.2.2 Water saturation and cementation

One of the purposes of the bentonite buffer is to prevent the canister from being exposed to a direct flow of groundwater and to filter out as much as possible of corrosive ions and microorganisms. The idea is that the bentonite should absorb groundwater and swell until it fills all voids and further penetrate into fractures in the surrounding rock. At the same time, its density should increase to a level of about 2 kg/dm^3 (at least in the deposition holes), making the buffer very tight.

Due to the decay heat from the canister, a temperature gradient will be created through the buffer in the deposition hole¹³, i.e. the temperature in the buffer will vary with the distance to the canister. This temperature difference is expected to persist for over 1,000 years and will of course influence the mechanism for water saturation of the bentonite. The water enters from the colder side nearest the surrounding rock and is “sucked” into the bentonite by a combination of processes. However, the bentonite is not quite dry from the start, since the clay must contain quite a bit of moisture in order to be compacted into strong blocks and rings. The water in the bentonite nearest the hot canister will move out towards the rock, while the cold water will be drawn inwards. It is in this complex environment with water transport in different directions and a variable temperature gradient that the water saturation of the bentonite buffer will take place. The impurities and minerals that are

¹³ TR-09-29.

present in the bentonite and have relatively high solubility can be expected to be transported by the water. The impurities that are more soluble in hot water will move outward from the canister, while those that are more soluble in cold water will move inward. At numerous places in the front between the hot and the cold water, secondary precipitations will occur, a process usually called cementation which affects the mechanical and chemical properties of the bentonite. SKB is currently conducting research on the mechanical consequences of cementation.¹⁴

3.2.3 Transport of corrosion products

Interaction between corrosion products from copper and bentonite¹⁵ under conditions similar to those expected in the final repository have been studied in a POSIVA project from 2008.¹⁶ Atacamite (copper(II) chloride hydroxide) was used as a model for a corrosion product that was in contact with compacted bentonite for nearly 3 years. Copper(II) ions from the corrosion product were transported less than 1 mm into the bentonite regardless of temperature. This can be compared with the results of equivalent processes in SKB's LOT project, when corrosion products from heated copper tubes were transported several centimetres into the surrounding bentonite. The different results may be due to the fact that a heated copper tube gives rise to a temperature gradient that leads to the simultaneous transport of water and corrosion products from the surface. Corrosion products from the copper tube accompany the heated water out into the bentonite and are therefore transported a longer distance.

Under conditions in the final repository, similar water transport is only likely to occur during the initial period when the bentonite is moist and the environment is oxidizing, after which it will cease when the temperature has evened out, provided a sudden breakthrough of water has not occurred in the buffer.

¹⁴ TR-10-41.

¹⁵ Bentonite of type MX-80.

¹⁶ POSIVA is a Finnish counterpart to Swedish SKB.

3.2.4 The bentonite affects the canister

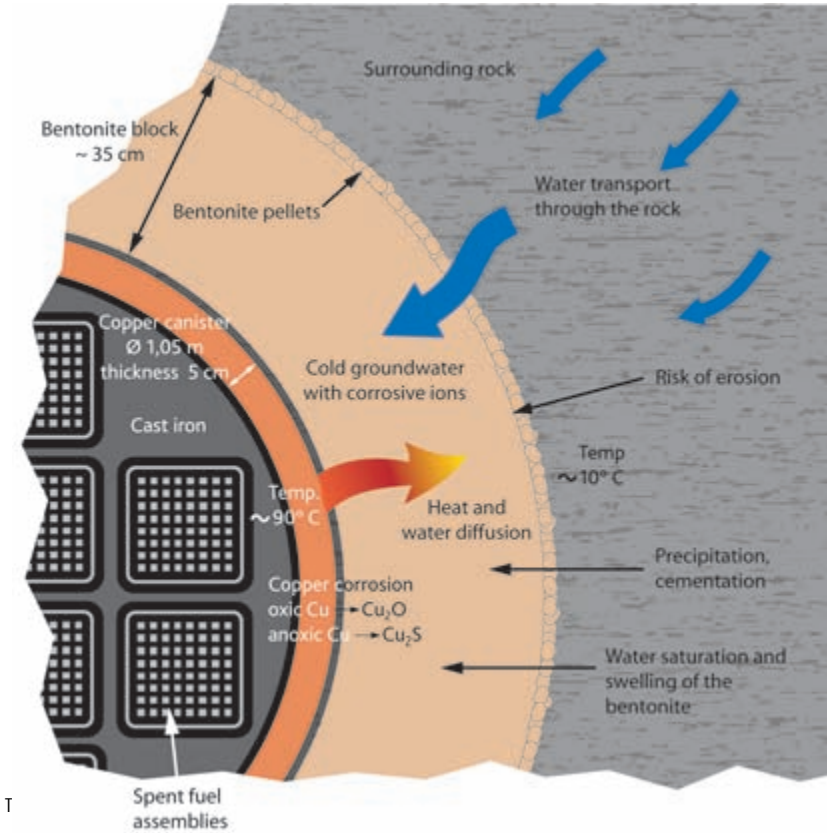
The mechanism for water saturation of the buffer is thus relatively complex and is further complicated by the species (complex ions) present in the groundwater, i.e. mainly chlorides, calcium ions and carbonate and sulphate ions, all of which have unique pathways to spread into the bentonite. The groundwater cannot be expected to be homogeneously distributed in the outer parts of the buffer; the bentonite in the vicinity of water-bearing fractures in the rock will become water-saturated first and swell. If the distribution of water is very uneven, this could lead to stresses on the canister due to the fact that it is subjected to varying pressure and strain, which can in turn affect the canister's creep and corrosion properties. In its previous reports, the Swedish National Council for Nuclear Waste has urged SKB to conduct research on stress corrosion cracking.¹⁷ If the difference in water saturation is great in the bentonite nearest the canister, the environment will vary on different parts of the surface and there may be a risk of pitting. The question is how extensive it can become before the environmental differences nearest the canister have been evened out.

3.2.5 Freezing of bentonite

SKB has carried out a large number of laboratory experiments where water-saturated bentonite samples have been exposed to temperatures in the range -10°C to +25°C at the same time as the swelling pressure has been measured. The samples have varied with respect to bentonite type (sodium or calcium bentonite) as well as smectite content and density. It is naturally a very important investigation, since the temperature in the repository will vary, both with time and with depth in the repository. The conclusion is that the buffer will not freeze during the life of the repository, since ice only forms in the bentonite below +5°C, and the lowest expected temperature at repository depth is around -2°C. The bentonite in the backfill in tunnels, ramp and shafts could freeze, but this is not a problem since the freeze/thaw process has proved to be completely reversible.

¹⁷ See e.g. SOU 2010:6.

Figure 3.1



3.3 Conclusions of the Swedish National Council for Nuclear Waste

3.3.1 Copper corrosion

It is highly gratifying that SKB is continuing its research on copper corrosion in contact with water under both oxic and anoxic conditions (both with and without oxygen).

The credibility of the research is a key issue in conjunction with the issue of the long-term function of the engineered barriers. In this context the Council would once again like to reiterate the need of SKB-independent research, preferably with funding from other

sources. The role of research will continue to be important, even after an application has been submitted for the final repository.

The corrosion mechanisms for copper under oxygen-free conditions are of particular interest, since these are the conditions that will ultimately prevail in the repository. Studies under repository-like conditions are very valuable, not least with incomplete and uneven water saturation of the bentonite, since there is a risk that local corrosion cells might be created due to varying availability of oxygen and transport of reactive substances to the canister. Uneven water saturation of the bentonite could also give rise to creep in the copper metal and deformation of the canister. The Council recommends continued research in the area.

The Council believes that the research should not be limited to pure oxygen-free water, but also include ions in the groundwater that can stabilize copper ions (Cu^+ and Cu^{2+}) that are formed in the process, i.e. above all different types of negatively charged sulphur-containing ions (anions) and chlorides.

The experiments that have been initiated by SKB and are being conducted at Uppsala University, among other places, to evaluate the results of Hultquist *et al.* appear to have a promising design and will hopefully provide information on whether these results can be replicated. It should be pointed out that the initial conditions can in many ways be decisive for the results, i.e. the purity and structure (grain size) of the copper metal, how the surfaces of the foils have been cleaned prior to the experiment and the time from cleaning to contact with water. The purity of the water is of course also a key factor, including the quantity of dissolved gases from the atmosphere and possible impurities from ion exchanger resins and/or distillation apparatus.

The results of Hultquist *et al.* entail that an as-yet-unknown corrosion product is formed with a composition similar to copper hydroxide but whose properties have not been established. In its most recent state-of-the-art report¹⁸, the Swedish National Council for Nuclear Waste described a similar reaction product together with hydrogen gas evolution¹⁹. Such a reaction is described in the literature²⁰ and in general, the importance of chemical reactions on copper surfaces in conjunction with corrosion are poorly investigated and should be further studied. These reactions include

¹⁸ *Nuclear Waste State-of-the-Art Report 2010 – challenges for the final repository programme.*

¹⁹ $\equiv\text{Cu} + \text{H}_2\text{O} \Leftrightarrow \equiv\text{CuOH} + \frac{1}{2}\text{H}_2$, where \equiv designates the surface.

²⁰ e.g. E. Protopopoff and P. Marcus; *Electrochimica Acta*, 51, 408 [2005].

adsorption and precipitation on the surfaces and also underscore the importance of the surface-chemical double layer that is created when the bipolar water molecules near the surface arrange themselves to counteract the charge on the surfaces. The importance of the surfaces for corrosion of copper can be evaluated by increasing the surface area, which can be done by using copper powder. It can be pretreated in different ways by exposure to different environments (for example oxidation), after which the corrosion rate and its extent can be compared. There is a value in distinguishing between the type of corrosion that has been initiated by the appearance and microstructure of the surfaces and the reactions with the “bulk metal” that are driven by thermodynamic relationships in the copper/water system (Cu/H₂O).

In-depth studies of stress corrosion cracking and how the strength of copper is affected by hydrogen absorption continue to be urgent.

3.3.2 Processes in the bentonite

It is the opinion of the Swedish National Council for Nuclear Waste that research concerning the properties of the bentonite for specific use in the final repository should continue. This applies to bentonite in the form of compacted blocks, rings and pellets in both buffer and backfill. In its first state-of-the-art report, the Council commented on the challenge to the buffer and backfill posed by the possibility of bentonite erosion²¹.

Many of the properties of the bentonite buffer are dependent on its composition and content of different types of impurities. As described above, the composition of the bentonite buffer influences a number of mechanical and chemical properties, and the Council has in previous reports urged SKB to study and describe this in greater detail. Other important factors for optimizing the properties of the buffer include the pretreatment to which the bentonite is subjected before it is placed in the repository. This includes grinding, additives and compaction, all of which affect the properties in different ways. The pretreatment also provides an opportunity to modify the bentonite if desired. It could be worth testing if an addition of, for example, a limited quantity of Cu⁺ ions to the bentonite could prevent or at least counteract possible

²¹ SOU 2010:6e.

oxidation of the copper canister. In summary, the copper corrosion reaction can be expressed as a chemical equilibrium, $\text{Cu} \rightleftharpoons \text{Cu}^+ + \text{e}^-$, and a small amount of added CuCl (on the right side of the equilibrium expression) makes the copper metal (Cu on the left side) more stable.

In its previous reports, the Swedish National Council for Nuclear Waste has described the water saturation process as an important parameter for the future function of the buffer²². A very dry rock (which is expected in Östhammar) means that water saturation takes a very long time, and the bentonite nearest the copper canister will dry out to a high degree, which will affect the buffer's strength and other chemical/physical properties. As the environment nearest the canister becomes drier, the thermal conductivity through the buffer will probably decline, which means that a higher temperature will be maintained for a longer time. This in turn means that the buffer may become more brittle, which has also been observed by SKB²³. The question is whether the compacted bentonite will hold together or whether it will fall apart on drying, and how this will affect the properties of the buffer before and after it has been water-saturated. This should be an area for SKB's further development work.

The experiments that have been done on how the bentonite's swelling pressure is affected by freezing are highly relevant in view of the long-term function of the repository. The question is whether the conclusion that freezing does not pose a problem is quite correct. If the outside temperature falls, the backfill nearest the ground surface will freeze first. The water that has been absorbed by the bentonite contains solutes and salts, which will be separated from the water and concentrated when the bentonite freezes. The longer the frozen period lasts the more pronounced this process will be. When the bentonite subsequently thaws and meltwater runs down into the repository, there is probably a risk that the bentonite, and thereby the properties of the backfill, will be affected negatively.

Studies should be carried out where bentonite is repeatedly allowed to freeze in contaminated groundwater and then thawed.

²² SOU 2007:38, SOU 2008:70.

²³ TR-10-41.

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4 Legal, technical and social science perspectives on the alternatives issue

The issue of alternatives always comes up in some form in different parts of the process of planning of societal changes. What alternatives are available? Which are considered feasible or reasonable to implement? When will they be presented? These are questions that all actors in a planning process ask themselves and try to answer – consciously or unconsciously.

When it comes to the final repository for spent nuclear fuel, questions concerning alternative technology and alternative sites have recurred since the early 1970s. The question of the geological premises for site selection has been addressed in another part of this state-of-the-art report. This section deals with legal, technical and social science perspectives on the issue of alternative methods to KBS-3.

On the eve of SKB's licence application for construction of a final repository for spent nuclear fuel, it is very relevant to focus the question on the alternatives to KBS-3. It is relevant from a democratic perspective and from the perspective that the body of knowledge available to the environmental court and the Government should be comprehensive and permit an "overall assessment". How alternative technologies and methods for final disposal are handled in the planning process and how the site of the final repository has been selected are central questions at this stage.

Ever since its first state-of-the-art report in 1986, the Swedish National Council for Nuclear Waste has devoted significant attention to the alternatives issue. It really involves two different questions:

1. what alternatives to KBS-3 should be considered by SKB?
2. what requirements should such an alternatives report satisfy?

In recent years the discussion has centred mainly on the alternative of Deep Boreholes (for example at the Swedish National Council for Nuclear Waste's alternatives seminars in 2006, the seminar on deep boreholes in 2007, the state-of-the-art report for 2007 and Karl Inge Åhäll's report to the Swedish National Council for Nuclear Waste in 2010).

In the Council's viewpoints on SKB's preliminary environmental impact statement (EIS 2010) it is stated that "the information that is presented in the environmental impact statement must be so comprehensive that it is clearly evident in all questions what SKB's standpoints are and what basis SKB has for these standpoints. *The Council finds that this is not the case when it comes to background information for assessment of environmental effects regarding long-term safety, description and assessment of alternative methods (including the zero alternative) and the basis for SKB's site selection.*"

The main purpose of this section is to present newfound knowledge on alternative methods since the state-of-the-art report for 2010. The section describes the current situation regarding:

1. interpretations of the legal requirements on an alternatives report
2. any new facts that have come to light regarding technologies and methods for final disposal, mainly the alternatives of Deep Boreholes and Partitioning and Transmutation (P&T)
3. the contributions of the social sciences to elucidating whether alternatives have been adequately handled in the planning process.

4.1 Legal aspects of the alternatives issue

Requirements on reporting of alternatives in conjunction with permissibility applications for activities are stipulated in the Environmental Code's provisions on environmental impact assessment. How the requirements are to be interpreted has been and is still a subject of discussion. The intention here is to shed light on the current situation regarding the legal interpretation of which alternative designs should be reported in conjunction with a licence application pursuant to the Environmental Code for a final repository for spent nuclear fuel.

4.1.1 The purpose of an environmental impact statement

An environmental impact statement should be included in the background material on which the examination of a licence application under the Environmental Code is based. According to the first paragraph of Chap. 6, Sec. 7 of the Environmental Code, an environmental impact statement shall, to the extent required in view of the nature and scope of the activity or measure, contain the information that is needed for the description to fulfil its purpose.

This purpose is to identify and describe the direct and indirect impact of the planned activity or measure on a) people, animals, plants, land, water, air, the climate, the landscape and the cultural environment, as well as on b) the management of land, water and the rest of the physical environment, and c) other management of materials, raw materials and energy. Another purpose is to enable an overall assessment to be made of this impact on human health and the environment.¹

It is clear from the travaux préparatoires (legislative history) of the Environmental Code that the work with an environmental impact statement should provide as good a basis as possible for decisions on activities or measures which can, jointly or severally, have an impact on human health, the environment, management of land and water, etc. The work should contribute to filling knowledge gaps, as well as to increased knowledge and insight on environmental, health and natural resource issues in the individual matter. The public's participation and opportunity to influence the environmental impact statement and the planned activity at an early stage is an important aspect in this context².

4.1.2 Alternative sites and alternative designs

If – as in the case of a final repository for spent nuclear fuel – the activity or measure is likely to have a significant environmental impact, the environmental impact statement shall always contain a report on alternative sites, if such are possible, and alternative designs.

In conjunction with this report, the applicant shall also explain why a given alternative has been chosen. The consequences of not

¹ Cf. Chap. 6, Sec. 3 of the Environmental Code.

² See Gov. Bill 1997/98:45 II p. 56.

implementing the activity or measure in any form – the zero alternative – shall also be described.³ The zero alternative entails making a comparison between the consequences of implementing the project referred to in the application and an expected future situation where the project has not been implemented. The zero alternative also provides a frame of reference for comparisons between different alternatives – in this case between building a final repository for spent nuclear fuel and continuing to interim-store the spent nuclear fuel.

Somewhat similar rules exist in Community law when a project is likely to have a significant impact on the environment. Thus, the developer shall, under stipulated conditions, provide an outline of the main alternatives considered by the developer and the main reasons for his choice, taking into account the environmental effects.⁴

Regarding the contents of the environmental impact statement, the requirement on a description of alternatives is directly expressed in the text of the law in cases where the activity or measure is likely to have a significant environmental impact. What the requirements of the law imply in greater detail is not specified, however.

The reasons refer to the Community rules and what is said there about an outline of the main alternatives. However, the legislator has referred to the requirement on a description of the alternatives as fundamental and emphasized that not just alternative designs but also – where applicable – alternative sites must be specified if the environmental impact statement is to fill its function.⁵

The requirement on a description of alternatives must be viewed in the context of the general rules of consideration in Chap. 2 of the Environmental Code⁶. An applicant must show compliance with the obligations following from the chapter. These include the obligation to take precautionary measures and select a site that is suitable in order that the purpose is achieved with minimum damage and detriment to human health and the environment.⁷

The alternatives report shall serve as a basis for an assessment of the application pursuant to Chap. 2 of the Environmental Code. An environmental impact statement shall in this way contribute to

³ Cf. Chap. 6, Sec. 7, paragraph 2, point 4 of the Environmental Code.

⁴ see Article 5 in Council Directive 85/337/EEC of 27 June 1985 on the assessment of the effects of certain public and private projects on the environment, in wording according to Directive 97/11/EC of 3 March 1997.

⁵ See Gov. Bill 1997/98:45 Part 1 p. 290 and Part 2 p. 63.

⁶ NJA 2009 p. 321 (Supreme Court 10 June 2009, case no. T 3126-07, p. 7).

⁷ See Gov. Bill 1997/98:45 Part 2 p. 63.

ensuring that an activity, if it is implemented, leads to as little adverse environmental impact as possible.⁸ Furthermore, there is a link to the earlier consultation, in that the applicant may have reason in the environmental impact statement to treat realistic alternatives that emerge from the consultation⁹.

4.1.3 Early consultation with the County Administrative Board

The County Administrative Board has, according to the Code, been given an opportunity to determine in the individual case the scope and focus of the alternatives report. According to the provisions of the Code, the County Administrative Board may, within the framework of the consultation procedure, require that other comparable ways to achieve the same purpose shall be presented¹⁰.

In its decision of 30 December 2002 regarding a possible deep repository for spent nuclear fuel at Forsmark, the County Administrative Board in Uppsala County makes the following assessment:

Beyond a presentation and assessment of realistic alternative methods for final disposal of the spent nuclear fuel as waste within the framework of the environmental impact statement, the County Administrative Board has not found reason to require a special report of “other comparable ways of achieving the same purpose” according to Chap. 6, Sec. 7, paragraph 2 of the Environmental Code, when alternative designs are presented in the environmental impact statement.

The reasons given by the County Administrative Board for this assessment is:

that the possibility of utilizing the spent nuclear fuel as a resource for the production of electric power is not realistic, given Swedish policy and legislation bearing on nuclear activities.

Thereby, according to the County Administrative Board:

the requirements that need to be imposed on a broad alternatives report in the environmental impact statement can be based on the provision in Chap. 6, Sec. 7, paragraph 1, point 4, of the Environmental Code, which prescribes a description of alternative sites and alternative designs.

⁸ See Gov. Bill 1997/98 Part 2 p. 56.

⁹ NJA 2009 p. 321 (Supreme Court 10 June 2009, case no. T 3126-07, p. 7)

¹⁰ Cf. Chap. 6, Secs. 4 and 5 of the Environmental Code.

Notwithstanding the decision of the County Administrative Board, the question of alternative methods can be brought to court, but then within the framework of the material assessment of the licence application.

4.1.4 Requirements on alternatives during a consultation procedure

The environmental impact statement shall be preceded by a consultation procedure between the activity operator, regulatory authorities and private citizens¹¹. The consultation shall comprise a part of the work with the environmental impact statement, and there shall be an opportunity for the various stakeholders to influence the form and content of the EIA via their viewpoints¹². The consultation shall be held at an early enough stage that even more fundamental changes in the project are feasible.

The environmental impact statement constitutes a public report on the impact which a planned activity may have on the environment. Notification shall therefore be given when an environmental impact statement has been prepared in a case or matter, and the description shall be made available to the public who shall be given an opportunity to express an opinion before the case or matter is examined.¹³

In a relevant judgement, the Supreme Court has ruled on the importance of the alternatives report in the environmental impact statement¹⁴. The case concerned the construction of a dam. The court arrived at the conclusion that the environmental impact statement presented in the application was not acceptable in view of the fact that alternative designs of the dam that had emerged during the consultation process had not been presented in the environmental impact statement. The application should thus be rejected. An acceptable environmental impact assessment is a prerequisite in an application case.

A factor of importance for the judgement in question was that the applicant had not described in the environmental impact statement any alternatives to the design of the main dam with their

¹¹ Cf. Chap. 6, Sec. 4 of the Environmental Code.

¹² See Gov. Bill 1997/98:45 Part 1 p. 286 ff.

¹³ Cf. Chap. 6, Sec. 8 of the Environmental Code, cf. article 6.2 in the 1985 EEC directive in its 1997 wording.

¹⁴ NJA 2009 p. 321.

impact on the environment, despite the fact that other options for the design of the dam had been suggested during the consultation process. The applicant had not explained why other alternatives had been rejected.

The applicant did claim that there were no alternatives in the true sense of the word. According to the Supreme Court, however, the environmental impact statement did not provide sufficient evidence for this claim.

According to the Supreme Court, it is important that the applicant not be reluctant to see alternatives to the solution recommended by the applicant and that the material be sufficient so that other stakeholders and ultimately the deciding court have a basis for their own judgement¹⁵. According to the Supreme Court, a minimum requirement is that the applicant describe different options and explain why an alternative has not been further pursued and state on what grounds the applicant has arrived at the conclusion that there are no alternatives.

The Supreme Court contended that this does not mean that the applicant can limit his description to alternatives that have emerged during the consultation process; ultimately it is the applicant who bears responsibility for ensuring that the description contains all the necessary information.

4.1.5 Alternatives offered during SKB's consultation procedure

In a letter to SKB dated 1 December 2006, SKI stated that the environmental impact statement that will be included in the company's application pursuant to the Act (1984:3) on Nuclear Activities (the Nuclear Activities Act) and the Environmental Code should, in addition to the main alternative and the zero alternative, also describe the alternatives that SKB has studied within the framework of its RD&D programme according to Section 12 of the Nuclear Activities Act as well as the reasons why the alternatives have not been further studied. The alternatives referred to in this connection include Deep Boreholes and Partitioning and Transmutation.

The county administrative boards in Uppsala and Kalmar counties have developed a common view of the consultation and EIA

¹⁵ NJA 2009 p. 321 (Supreme Court 10 June 2009, case no. T 3126-07, p. 7).

issues that should serve as a basis for the licensing of an encapsulation plant and a final repository. The county administrative boards believe it is important to provide an exhaustive account of alternatives to the KBS-3 method and why certain alternatives are considered favourable and others have been rejected¹⁶.

In a statement of comment to SKB, the County Administrative Board in Uppsala County presents its viewpoints on the alternatives report in a coming environmental impact statement¹⁷. The statement is submitted in connection with SKB's background material for consultations on the encapsulation plant and the final repository for spent nuclear fuel¹⁸. The County Administrative Board states that the alternatives report in the environmental impact statement should describe all possible alternative sites and designs that are being or have been considered in SKB's consultations or research and development work. Such a general account should, according to the County Administrative Board, be so comprehensive that it permits an integrated, comparative assessment of the advantages and disadvantages of the alternatives, with special consideration given to effects on human health and the environment as well as the management of natural resources, in the light of the fundamental values expressed in Chap. 1, Sec. 1 of the Environmental Code. In the judgement of the County Administrative Board, the alternatives report should also contain an analysis of the possibilities of reducing the quantity and radiotoxicity of the waste (for example by partitioning and transmutation), since this could reduce the risk of environmental impact.

The Swedish NGO Office for Nuclear Waste Review, MKG, has stated that the organization wants SKB to compare different geological methods, such as Deep Boreholes, with the KBS-3 method. Partitioning and Transmutation (P&T) should also be included in the alternatives report. As far as the site of the final repository is concerned, MKG says that all sites discussed during SKB's feasibility studies should be included in the report. The review of site selection should focus on the environmental issues. SKB should thereby describe which environmental judgements SKB has made in rejecting certain sites and how a final repository

¹⁶ See report 2006:1 from the Swedish National Council for Nuclear Waste (KASAM), p. 20 ff.

¹⁷ Dnr 559-6890-06.

¹⁸ SKB 2006-05-11, reference EIA/2006/19.

in the interior of the country compares with a repository on the coast¹⁹.

Friends of the Earth and the Swedish Anti Nuclear Movement, MILKAS, state that they want to see an alternative where the radioactive material is kept in dry rock year for a few hundred years to permit the exploitation of any advances in technology, for example partitioning and transmutation, that may occur.²⁰

4.1.6 Summary

An acceptable environmental impact statement is a prerequisite for examination of a licence application.

In a judgement from 2009, the Supreme Court explained that an environmental impact statement is not acceptable if the alternative designs discussed during the consultation process have not been described in the environmental impact statement. According to the Supreme Court, a minimum requirement is that the applicant describe different options and explain why an alternative has not been further pursued and state on what grounds the applicant has arrived at the conclusion that there are no alternatives.

The alternatives to the KBS-3 method recommended by SKB that have been put forward during the early consultation include a method involving deep boreholes. Other alternatives involve reducing the quantity and radiotoxicity of the waste, for example by partitioning and transmutation.

If any or all of these alternatives are judged by SKB in a coming application to be unrealistic or for other reasons unfeasible, SKB should provide valid and relevant reasons for this judgement.

4.2 Technical and scientific aspects of the alternatives issue

In addition to the legal aspects, the scientific and technical development of alternative methods is of fundamental importance in the nuclear waste issue. The Swedish National Council for Nuclear Waste's Review of the Swedish Nuclear Fuel and Waste Manage-

¹⁹ See report 2006:1 from the Swedish National Council for Nuclear Waste (KASAM), p. 23 ff.

²⁰ See report 2006:1 from the Swedish National Council for Nuclear Waste (KASAM), p. 24 ff.

ment Co's (SKB's) RD&D Programme 1998²¹ dealt with different strategies for management of the high-level nuclear waste. In the Council's state-of-the-art report for 2007 they were discussed in detail in a special chapter.²² Since then, new knowledge has been forthcoming, particularly with regard to the alternatives *Deep Boreholes* (deposition in boreholes 2–4 km deep in the Swedish bedrock), *New Reactor Technology* (new options for both future nuclear power and disposal of spent nuclear fuel) and *Partitioning and Transmutation* (transformation of long-lived radionuclides to more short-lived ones by neutron irradiation).

4.2.1 Deep Boreholes

The method Deep Boreholes entails that the waste is enclosed in canisters, which are then lowered into boreholes to a depth of 2–4 km in the Swedish bedrock. The main virtue of this method is that the groundwater flux at this depth is very limited and that it would take such a long time for the groundwater to transport the radioactive substances from the canisters up to the surface that their radiation would have decayed to a harmless level before they reach the biosphere.

Current research

SKB gives its opinion of Deep Boreholes as an alternative to the KBS-3 method in RD&D Programme 2010: "SKB's stands by its assessment from previous RD&D programmes: that disposal in deep boreholes is not a realistic method for final disposal of spent nuclear fuel."

When the application for the KBS-3 method is submitted in 2011, a report presenting a comparison between the KBS-3 method and disposal in deep boreholes is promised.

RD&D Programme 2010 presents three new reports on Deep Boreholes. Two reports are from the UK²³, which make positive assessments of the possibilities of drilling boreholes down to the depths (more than 3,000 metres) and with the diameters (more than 500 millimetres) required. Problems with lining and sealing of

²¹ SOU 1999:97.

²² SOU 2007:38, Chap. 3.

²³ Beswick 2008 and Baldwin, Chapman & Neall 2008.

the boreholes are also discussed in the reports. “The overall conclusion in the study is that the Deep Boreholes concept may, under certain circumstances, be a credible option for the UK, but that a great deal of development work would be required on both drilling technology and deposition technology.” (A report from Canada²⁴ also mentions the extensive research that will be needed to make a comparison between Deep Boreholes and the KBS-3 method.) The third report comes from the USA²⁵ and makes a positive assessment of Deep Boreholes as a method for safe disposal. The report recommends that a full-scale pilot project be undertaken in order to fully explore the viability of a borehole disposal concept.

Summary

A Swedish summary of the state-of-the-art was also written in 2009.²⁶ This report points out that R&D efforts are needed in three areas in order to evaluate whether Deep Boreholes (DB) is an alternative to the KBS method. It is necessary to:

- prove that the physical prerequisites for the method exist in Sweden.
- upgrade knowledge of the groundwater’s density stratification so that there is at least a relevant hydrogeological model of normal bedrock Swedish bedrock down to 5 km depth.
- upgrade knowledge of drilling and deposition technology and the repository’s long-term function so that comprehensive and safety-related comparisons can be made, which is the goal and purpose of the alternatives report.

These reports show that other actors see Deep Boreholes as a possible alternative for final disposal of spent nuclear fuel, and that only in-depth research can determine whether this method can satisfy the tough safety requirements on a final repository. It is therefore essential that SKB clarify in its application why they view Deep Boreholes as “not a realistic method for final disposal of spent nuclear fuel.”

²⁴ Jackson & Dormuth, 2008.

²⁵ Brady et al. 2009.

²⁶ Åhäll 2009.

The dramatic mining accident in Chile in August 2010, and the successful rescue action that was carried out, suggest that advanced technology is available. The 33 miners were rescued via a 702 metre deep borehole with a diameter of 66 centimetres.

Swedish research in the area can also be expected to contribute to technological progress. The Swedish Deep Drilling Program, SDDP, was started in the spring of 2007 and currently involves six scientific projects with around 40 Swedish and an equal number of foreign researchers. The Swedish Research Council has previously given the program planning grants but has now granted funds for purchase of a drilling rig. Provided that SDDP's working group receives the financial support that is needed, a first deep borehole in "Swedish" bedrock will be realized in 2011 or 2012²⁷.

4.2.2 New reactor technology – importance for retrieval and disposal of spent nuclear fuel

In recent years we have seen increased spending on research on reactor technology and the nuclear fuel cycle in the world, the EU and Sweden. This research is revealing new possibilities both for future nuclear power generation and for management of spent nuclear fuel. Within a relatively near future, important decisions will be taken in many countries regarding the future of nuclear power, and if it is decided to continue using nuclear power, reactor types and fuel for them must also be chosen. This will in turn have more or less far-reaching consequences for how a repository for spent nuclear fuel is best designed.

Developments in the reactor area are closely linked with the development of methods for Partitioning and Transmutation (P&T), which is one way to deal with the waste in order to reduce its radiotoxicity and volume. On a general level, these issues are therefore associated with the question of retrievability of the spent nuclear fuel.

A very brief account is given below of what importance the future trend in the reactor area may have for the design of the Swedish repository for spent nuclear fuel²⁸.

²⁷ http://www.sddp.se/sites/default/files/SDDP_ScienceTechnologyPlan_2010-print.pdf

²⁸ Energy production by nuclear fusion or in fission reactors that use thorium as a fuel instead of uranium are two types of future technologies for nuclear energy production that are not taken into account in this report, but that should not be overlooked when the time is ripe.

New reactor technology

Current research on reactor technology is expected to lead to nuclear reactors based on other principles than today's traditional light water reactors (LWRs). Different principles for the nuclear fuel cycle are conceivable in these Generation IV reactors. A recently published report from the Massachusetts Institute of Technology²⁹ recommends keeping these various options open awaiting a method for management and disposal of spent nuclear fuel from light water reactors.

A common feature of the different alternative General IV reactors is that a much larger quantity of energy, up to 50 times more, can be extracted from the same quantity of fuel. With today's reactor technology, however, the cost of uranium is only a very small fraction of the total cost of the generated electricity, and economic incentives are at present lacking for conserving uranium as a limited natural resource. For this reason it is judged that light water reactors will probably be the primary choice for nuclear reactors during the present century. In a perspective of about 100 years, however, the cost of uranium could become a strong incentive to introduce Generation IV reactor technology in more extensive commercial operation. Another incentive may arise if it is found that this technology makes it possible to greatly improve safety viewed over the whole chain from fuel fabrication to spent fuel disposal.

A Generation IV reactor can be run on spent fuel from light water reactors after some form of reprocessing. If this is an economically viable method compared with using fuel made from freshly mined uranium, the spent fuel from light water reactors will constitute an economic resource.

The waste from Generation IV reactors

The waste produced by Generation IV reactors will differ considerably in its composition from that obtained from light water reactors. Its composition will also be dependent on what type of reactor has been used, which is also one of the factors that should be taken into account in the evaluation. Generally, however, the more efficient utilization of the fuel in Generation IV reactors

²⁹ MIT Interdisciplinary study, *The Future of the Nuclear Fuel Cycle*, 2010.

means that the waste volume is reduced considerably. The fraction of radionuclides with a very long half-life is also much lower, which means that the requirement on durability is not the same. Long-term safety could possibly be further improved due to the fact that the smaller fraction of long-lived fission products expected to be found in the waste is separated from the rest of the waste. In order to better analyze the short-term radiological risks from this waste, further research is needed on the possible nuclear fuel cycles.

The spent fuel from the Generation IV reactors is not in itself a potential resource, since it will not necessarily be possible to extract significantly more energy from it. Since the volume is also relatively small, it would be well suited for final disposal in a deep borehole.

It is worth noting that even if the Generation IV reactors become reality, there will still be a need for a repository for waste from today's light water reactors.

4.2.3 Partitioning and transmutation

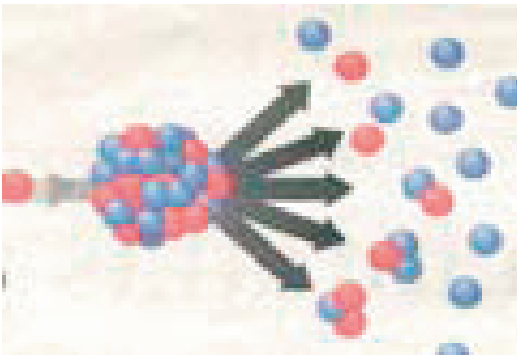
The term transmutation means transforming one element into another, or one isotope of an element into another isotope. This is something which man has tried to do without success for centuries in order to make gold from lead. The purpose now is to transform radioactive isotopes with a long half-life into isotopes with a shorter half-life, or to stable isotopes. The Swedish National Council for Nuclear Waste's state-of-the-art report from 2004 gives a detailed account of the principles and different methods for P&T³⁰. The present report therefore gives only a brief account of the method and the current state of research.

An element is defined by the number of protons in its atomic nucleus. Different isotopes of an element have different numbers of neutrons in the nucleus. In order to transform the element, a chain reaction has to be initiated that changes the number of protons and/or neutrons in the nucleus. One method to do this is to bombard the element with particles, for example neutrons or protons. If the particles have sufficiently high energy, the heavy atomic nuclei can be split into several smaller fragments, a process called spallation. Ions heavier than protons are often used for this. This splits the heavy transuranic nuclei into smaller fragments. The

³⁰ Nuclear Waste State-of-the-Art Report 2004, Chapter 8.

lighter nuclei obtained from the spallation (nucleus-splitting process) are normally relatively short-lived radioactive isotopes or stable elements (see Figure 3.1). This is the method usually referred to as “accelerator-driven transmutation” or “accelerator-driven spallation” (ADS). Another method is to bombard the fuel with neutrons in a nuclear reactor. However, in order for this to work, a reactor is required where the energy of the neutrons is higher than in a conventional reactor. For this reason, such a reactor is cooled with liquid helium or gas, such as helium, since water, which is normally used for cooling, slows down the neutrons.

Figure 4.1 Schematic illustration of spallation (the nucleus-splitting process). When high-speed protons (red spheres) from the accelerator collide at high speed with lead and bismuth nuclei in the centre of the sub-critical reactor, the nucleus splits into several fragments, releasing a large number of neutrons (blue spheres).



Transmutation by irradiation must be preceded by a chemical or mechanical separation (partitioning) of the different elements in the spent fuel.

The spent fuel rods consist for the most part of uranium, with ^{238}U as the predominant isotope. There are also heavy elements, called transuranics (actinides), formed during neutron irradiation of the fuel, along with stable and radioactive fission products (the remains of the nuclear fission), see Figure 3.2. The fission products generally have half-lives of less than 100 years, with two important exceptions: ^{129}I and $^{99\text{m}}\text{Tc}$. Many of the transuranics have long half-lives, however, in the order of thousands to millions of years.

Figure 4-2. Schematic illustration of the fission process. A neutron is captured by a uranium atom, which becomes excited and is split (fissions) into two parts (fission products). At the same time, a number of neutrons are emitted.



Current research

Like research on new nuclear technology, research on P&T is being conducted both in Sweden (KTH, Chalmers and Uppsala University) and in the EU's Seventh Framework Programme. Japan and Russia also have research programmes, and in the USA research is being resumed in the field after a long period of inactivity. (The USA has continuously conducted research on the fourth generation of reactors, for example Idaho Falls VHTR). The Swedish Research Council recently allocated a large sum to research on new nuclear technology and the fourth generation of reactors. This includes research aimed at developing industrial-scale methods for P&T, and work with this in Sweden is now entering a more intensive phase. It is worth noting that with this state grant, SKB is no longer the biggest funder of this type of research in Sweden.

EUROTRANS is a project that has been conducted within the EU's fifth and sixth framework programmes. The purpose has been to study how facilities for accelerator-driven transmutation could be designed. Two concepts for such facilities have been sketched and their design and function have been studied in detail:

- XT-ADS shows the principles for how an accelerator-driven transmutation facility could work. However, it is intended to be utilized for research rather than for industrial use.

- EFIT (European Facility for Industrial Transmutation), a design for a facility that could be utilized for transmutation on an industrial scale.

Within the Seventh Framework Programme, transmutation research has been integrated with research on the development of Generation IV reactors, where energy can be recovered from the waste. A platform called SNETP (Sustainable Nuclear Energy Technology Platform) has been created to bring different actors and stakeholders together. The nuclear power industry, research institutions, universities and others have an opportunity to identify and present the need for research. One of the primary tasks is development of the fourth generation of reactors, with fast neutrons and thus directly linked to the development of methods for partitioning and transmutation. In addition there are a number of other projects, including basic research aimed at gathering physical and technical data as a basis for further development in the area (ANDES³¹) and for development of chemical processes for separation (ACSEPT³²).

Retrievability

The issue of P&T is intimately associated with the issue of retrievability. Since separation (partitioning) of the various components of the waste is a necessary feature of the transmutation process, it is also associated with the issue of reprocessing of the spent nuclear fuel. Technologies similar to that used for transmutation of the waste may also be a prerequisite for the fabrication of fuel for the fourth generation of nuclear reactors.

If it is assumed that P&T will be developed at some point in the future into a functioning method for industrial-scale use, at the same time as the reactor technology is developed so that it can utilize the energy that can be extracted from the fuel more efficiently, the waste that is stored from today's reactors could be used as fuel, and moreover be transformed to isotopes with much shorter half-lives and lower radiotoxicity. Such a scenario assumes that it is technically and economically feasible to retrieve the waste for further processing. These question then arises as to what bear-

³¹ Accurate Nuclear Data for nuclear Energy Sustainability.

³² Actinide reCycling by SEParation and Transmutation.

ing the future possibilities and probability that this technology will be used has on the discussion of how the waste is to be stored. Interest in doing this could depend on the future availability of natural uranium from mines. Ideally, the necessary storage time for the waste could be reduced to 500–1 000 years, at the same time as its radioactivity is reduced by a factor of 100.

4.2.4 Summary

The traditional type of nuclear reactor, which uses ordinary water for cooling, will probably dominate energy production from nuclear power for the next 50–100 years. Technology development in the reactor and nuclear fuel field will be of decisive importance for whether or not the waste from the reactors of today and the near future can be regarded as a resource for future generations. The feasibility and advantages of using this resource must then be weighed against the different risks this entails for present and future generations.

Partitioning and transmutation does not eliminate the need for geological disposal, but the requirements on the engineered barriers will decrease, as will the volume of the waste. Nor will there be any economic incentives to retrieve the waste after transmutation in a Generation IV reactor. However, low- and intermediate-level waste is generated by the partitioning and transmutation processes, and these waste volumes will increase, requiring greater volume in these repositories.

The Council's conclusion regarding partitioning and transmutation can be formulated with reference to EURATOM, which, together with the European Commission, has summarized the transmutation issue as follows:

- Using nuclear fuel only one time does not appear to be a sustainable use of resources.
- Partitioning (separation) is required to reduce the volume and the radiotoxicity of the waste that needs to be stored.

- Transmutation is a way to reduce the total half-life of the waste and consequently the necessary storage time to a few hundred years.³³

At this stage, research on transmutation can be regarded as being in its infancy. Even if this research is successful, it is unrealistic to expect that it will be possible to build large-scale industrial facilities for the purpose sooner than in 25–30 years. It is also important to emphasize that this complicated technology, with relatively high investment costs, requires that development take place within the framework of a European collaboration. In order to enable Sweden to benefit from the gains made in this field, we will participate in the various research programmes. A national facility for Sweden appears today to be an unrealistic alternative.

4.3 The contributions of the social sciences to the elucidation of the alternatives issue

The Swedish National Council for Nuclear Waste has regularly returned to the question of the relevance of social science research for the nuclear waste issue. A report was published in 2007 with a survey of SKB's social science research programme and other independent research in the field³⁴.

The state of research was summed up as follows:

The social science research on the issue of nuclear waste is currently being funded for the most part by the actors in the sector, mainly SKB, but to some extent also by SSI and SKI. Only one research project with foundation funding and one project with EU funding have been identified (these funds have furthermore been granted to the same researchers). For natural reasons, SKB's social science research programme has the character of applied research, with a focus on the siting issue, but with an internal breadth. Including the research project started in 2006, issues relating to local decision processes, local socioeconomic factors and attitudes and opinions on nuclear waste in a broad sense can be said to be prioritized, although international perspectives are also included in the research programme. At the same time it can be noted that this research has not addressed issues that problematize the nuclear waste issue in a broader context of national democracy and economic policy. For example, the issue is not linked to the seemingly uncertain future of nuclear power in Sweden and to

³³ Bhatnagar 2008.

³⁴ KASAM Rapport 2007:5.

the country's national environmental policy and energy policy in general. Research outside that initiated in the sector has also focused to a great extent on processes on the local level, but with a clearer focus on the roles and strategies of the actors. But research is lacking here that raises the issue to a national context, for example including ethical, environmental law, environmental policy and energy policy problematizations.³⁵

SKB's social science research programme has been developed and broadened since 2007. Worth noting are Per Cramér's jurisprudential study "Assumption of responsibility in the back end of the nuclear fuel cycle", Magnus Frostensson's project "Industrial organization of the final repository" and Sven Ove Hansson's project "Ethical and philosophical perspectives on the nuclear waste issue" (all in Swedish only). Social science aspects of the alternatives issue have, however, not received any attention (although the subject is touched upon in Arne Kaijser's project "Resource or waste? International decision-making processes relating to spent nuclear fuel", in Swedish only).

In this context we want to concentrate above all on the lack of social science and humanistic research on the general societal and cultural aspects of the alternatives issue. There is virtually no research that sheds light on this issue³⁶. And this despite the fact that relevant social science theorizing on the interaction between science and society is not lacking. In this context we would like to indicate how such theorizing could shed important light on the alternatives issue.

4.3.1 A theoretical background

In "Re-thinking Science. Knowledge and the Public in an Age of Uncertainty" (2001), Helga Nowotny, Peter Scott and Michael Gibbons present a theory on an intensified interaction between scientists and various societal institutions. Previously scientists

³⁵ KASAM Rapport 2007:5, p. 40, in Swedish only.

³⁶ The prerequisites for a broad handling of alternatives in the planning process for final disposal of nuclear fuel are, however, dealt with in the research project "Communities of practice – the Swedish case of final disposal of spent nuclear fuel" (Tuija Hilding-Rydevik and Antoinette Wärnbäck, Swedish University of Agricultural Sciences, funded by Formas). The Swedish Environmental Protection Agency has also commissioned Tuija Hilding-Rydevik and Lars Emmelin to conduct a feasibility study of how the alternatives requirement in the Environmental Code's EIA requirements is handled, and whether this involves any problems (to be finished in early 2011).

spoke to society and society listened. Today society responds with demands on relevance and applicability. A new form of context-sensitive research is emerging.

One important change is the erosion of the collectivist belief systems that characterize the science system and generate the norms which bind it together. The result is less ‘segregation’ from, and more ‘integration’ with, society. Scientists now share their once exclusive systems for communicating information with these ‘outsiders’. One way of putting it is to say that the rising tide of individualism in society now has reached collectivist scientific communities.³⁷

This trend has many positive consequences. Political and economic institutions are demanding evidence-based research so that the quality of the material on which their decisions are based can be improved. At the same time, the research is becoming increasingly dependent on the limitations that define the political and economic trend. The perspectives are limited and the problematization of the scientific method is perceived as less important and perhaps even a “disrupting factor”.

Naturally, Nowotny’s and other theories do not stand unchallenged, but they do have relevance for the nuclear waste issue in general and the alternatives issue in particular. Have political and economic interests limited the perspectives and failed to take certain alternative methods for management of the spent nuclear fuel into account? Have the advantages of the planning premise – the KBS-3 method – been accentuated and the disadvantages not sufficiently explored?

4.3.2 Limitation of perspective in the nuclear waste issue?

The Swedish National Council for Nuclear Waste’s state-of-the-art report 2007:38e noted the importance of the AKA Committee’s report³⁸ for subsequent developments in the nuclear waste field³⁹. The KBS-1 method, which was developed in the late 1970s, was based on a geological multiple barrier system that was subsequently further developed by SKB into the KBS-3 method. According to a Government decision in 2001, this method was to serve as a planning premise for the coming site investigations. The KBS-3 method

³⁷ Nowotny et al. 2001, pp. 102 ff.

³⁸ *Använt kärnbränsle och radioaktivt avfall, SOU 1976:30, 31 and 41, Summary in English, “Spent nuclear fuel and radioactive waste”, SOU 1976:32.*

³⁹ SOU 2007:38, pp. 21 och 37.

entailed direct geological disposal of corrosion-resistant copper canisters surrounded by bentonite clay at a depth of about 500 metres in stable crystalline bedrock.

Direct geological disposal has become a main alternative in many other countries as well. (Finland, for example, has chosen the KBS-3 method with enclosure of the high-level waste in iron inserts surrounded by copper.) The Swedish regulatory authorities regulations are also clearly formulated with respect to the KBS-3 method.

From a social science perspective there is reason to pose the question as to whether political bodies, regulatory authorities and industry have formed a community of interests around the KBS-3 method that has hampered research and technology development on alternative methods.

The Swedish National Council for Nuclear Waste has a special responsibility to prevent a limitation of perspective in the nuclear waste issue and call attention to gaps in the technical and scientific body of knowledge resulting from such a limitation. SKB's dominance in nuclear waste research can also lead to a limitation of perspective. The question of how SKB's research is procured, published and critically analyzed is of central importance. The question of whether the Government and the regulatory authorities have taken sufficient notice of the need for social science research is also of importance. Have the Government's research bills, the regulatory authorities' appropriations directions and the regulations for the Nuclear Waste Fund given adequate attention to the social science perspective?

The Swedish National Council for Nuclear Waste has pointed out the need for independent nuclear waste research, e.g. in the social sciences, in different contexts.⁴⁰ It is interesting in this context to note that SKB also recently highlighted this need.

It could be contended – as some debaters have done – that the nuclear waste issue is of special national importance and should therefore be studied with funds from sources independent of the industry. The question could be posed as to why state research councils and regulatory authorities have not created their own programmes for funding research projects in such an important field as the social and societal dimensions of the nuclear waste issue. Such programmes could have complemented the research initiated by

⁴⁰ See e.g. Nuclear Waste State-of-the-Art Report 2007 (SOU 2007:38, s. 76).

SKB. But this has not happened. Nor has the field been highlighted as being of particular importance in the Government's current research bill. This is why a large portion of the social science and humanistic knowledge that exists today with regard to the nuclear waste issue in Sweden comes from SKB's social science research programme. We conclude that without SKB's funding, most of the research would not have been done⁴¹.

SKB's scientific committee further considers the knowledge gained via these social science research programmes to be reliable. They point out that SKB's research is carried out at universities, institutes of technology and research institutes inside and outside Sweden, and that it is of high quality and is conducted with high scientific integrity. With the insight the Swedish National Council for Nuclear Waste has had into the programme, there is no reason to question this claim. Nevertheless, the critical social science perspective on e.g. the alternatives issue could have been given greater attention. As early as 2007, the Council contended that it is unclear to what extent the social science research programme is aimed at filling existing knowledge gaps. This is still not clear.

The above arguments clarify and exemplify the need for research that sheds light on the premises for planning and decision-making, for example regarding alternatives, for activities relating to final disposal. Once again, the Council would like to call attention to the need for critically reflective social science research in the nuclear waste area.

4.3.3 Summary

Different social, political and economic processes may have led to a detrimental limitation of perspective regarding alternative methods. Even though SKB's social science research programme has produced important knowledge in the area, there is a lack of critically reflective social science research concerning the final disposal issue, for example regarding the premises for planning and decision-making, e.g. when it comes to alternatives.

⁴¹ Samhällsforskning 2004–2009. Teman, resultat och reflektioner. SKB. 2010, p. 8.

4.4 Conclusions of the Swedish National Council for Nuclear Waste

The legal, political, economic and democratic premises for identifying and evaluating different alternatives to final disposal of spent nuclear fuel are of fundamental importance for obtaining a reliable body of information as a basis for arriving at a safe and socially legitimate solution to the final disposal problem. Requirements on an alternatives report in the environmental impact statement have been raised, underscored and clarified in various court cases. This probably has consequences for the requirements on the contents of the environmental impact statement in SKB's application and the legal assessment of the EIS and the application.

Certain technical and scientific advances have been made when it comes to Deep Boreholes and Partitioning and Transmutation. However, there is no method today that can compare with KBS-3 in terms of being so thoroughly studied and having such an extensive knowledge base. Different social, political and economic processes may have led to a detrimental limitation of perspective regarding alternative methods. There is a lack of critically reflective social science research concerning the final disposal issue, for example regarding the premises for planning and decision-making, e.g. when it comes to alternatives.

The question of how alternatives are arrived at, accepted, legitimized and evaluated has technical, social and cultural aspects. The issue of alternatives in planning and decision-making for a final repository for spent nuclear fuel clearly shows the need for both technical and social science research independent of the direct needs of the activity operator.

The Swedish National Council for Nuclear Waste concludes:

- that from the legal perspective, greater importance must be attached to a report on alternative methods in the nuclear waste issue.
- that in its final licence application for construction of a final repository for spent nuclear fuel, SKB should clearly present and justify its standpoints regarding the concept of Deep Boreholes.
- that technology development in the reactor and nuclear fuel field will be of decisive importance for whether or not the waste

generated in the reactors of today and the near future can be regarded as a resource for future generations. Partitioning and transmutation does not eliminate the need for geological disposal, but the requirements on the engineered barriers will decrease, as will the volume of the waste. However, low- and intermediate-level waste is generated by the partitioning and transmutation processes, and these waste volumes will increase, requiring greater volume in these repositories.

- that if any or all of the alternatives to the KBS-3 method are judged by SKB in a coming application to be unrealistic or for other reasons unfeasible, SKB should provide valid and relevant reasons for this judgement.
- that it is urgent that resources be created to stimulate critically reflective social science research on the nuclear waste issue and the premises for planning and decision-making.

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

In the month of February every year, the Swedish National Council for Nuclear Waste publishes an independent review of the current state of the art 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.

This year's report *Nuclear Waste State-of-the-Art Report 2011—geology, barriers, alternatives* identifies issues that are controversial and in need of further elucidation: the geological premises for SKB's site selection, the durability of the barriers in the final repository environment, and legal, technical and social science perspectives on the alternatives issue.

The report can be downloaded at www.karnavfallsradet.se/eng and can also be ordered by emailing to karnavfallsradet@environment.ministry.se.



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