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KASAM
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Time for final disposal of nuclear waste

– society, technology and nature

An in-depth report supplementing KASAM's Nuclear Waste State-of-the-Art Report 2007 (SOU 2007:38)

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Swedish National Council for
Nuclear Waste (KASAM) M 1992:A

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Preface

In an in-depth elaboration of the 2007 report on the state-of-the-art in the field of nuclear waste (SOU 2007:38) the Swedish National Council for Nuclear Waste (KASAM) has found it suitable to use the time perspective as a common theme to address a number of different questions. This report has therefore been given the title *Time for final disposal of nuclear waste – society, technology and nature.*

This in-depth report contains contributions from persons active within KASAM as well as from some researchers who were specifically asked to contribute.

The report has been prepared by a working group coordinated by one of its members, Willis Forsling, KASAM. The persons connected to KASAM who also took part are Lena Andersson-Skog (member), Hannu Hänninen (expert), Gert Knutsson (member), Sören Mattsson (member), Jimmy Stigh (member) and Olof Söderberg (consultant). In addition, Professor Emeritus Bert Bolin and Professor Erling Nordlund contributed a section within their respective areas of expertise (the climate question and rock construction engineering, respectively).

KASAM has not taken a conclusive position on the contents of the different contributions but finds that overall they give a both complex and fascinating picture of the problems concerning nuclear waste.

Stockholm, May 2007

Kristina Glimelius
Chairperson

Content

1 Introduction

This in-depth report consists of a number of independent contributions which deal with different aspects of the nuclear waste issue but which have a common time perspective as a point of departure. It is not claimed that the questions which are dealt with here cover the whole area but they are judged to be of wide general interest.

In Chapter 2 a general overview is given of how the nuclear waste issue in Sweden has been dealt with since plans for the use of nuclear power began to take shape in the mid-1940s. The problems surrounding the nuclear waste issue are linked to our natural fear and loathing of the proliferation of nuclear weapons which has taken place over the last 60 to 70 years but the peaceful use of nuclear power over the last 30 to 40 years has also been far from uncontroversial. This has been reflected in the view on nuclear power and nuclear waste held by politicians and in public opinion in general and must be seen against the background of our increasing need of electric power and the debate on the global threat to our climate caused by the burning of fossil fuels. The views on nuclear power and nuclear waste, which are an unavoidable consequence of its use, have varied over time in Sweden. The report ends with some reflections on the work which will take place up until the 2060s. The time perspective is thus a little more than 100 years.

In Chapter 3 the time perspective is considerably shorter, around 20 years. Here the technical construction problems are dealt with on the assumption that a final repository using the KBS-3 method shall be built. The establishment and management of an underground repository have many similarities to the establishment of an underground mine and much experience may be drawn from this.

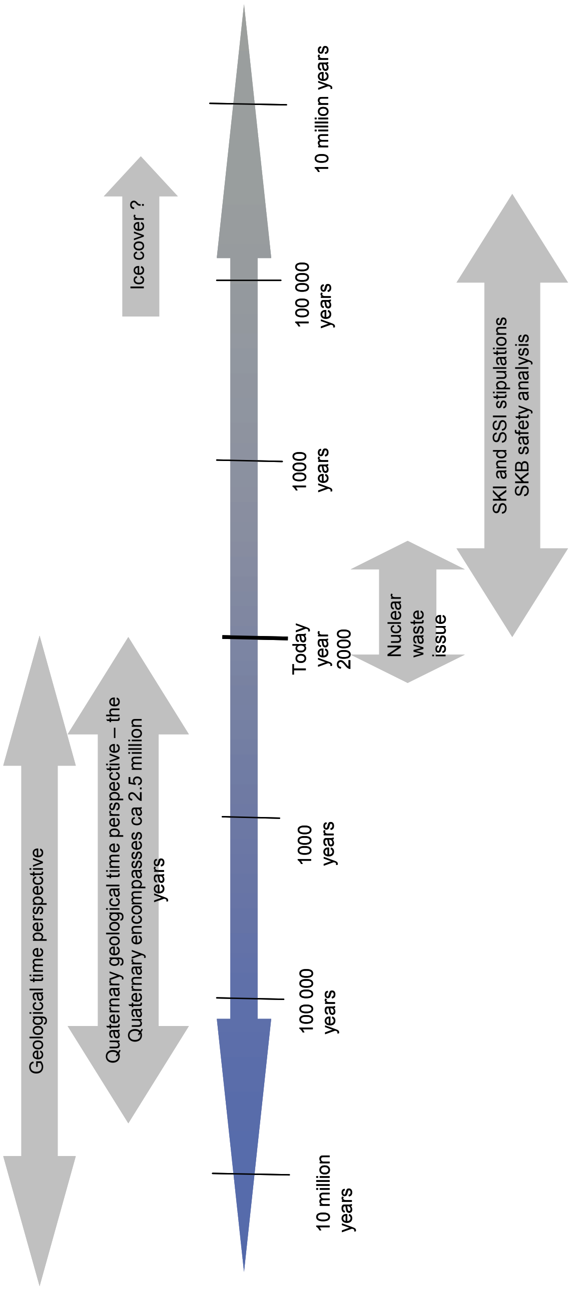
The question of technical barriers, copper canisters, the bentonite buffer and the backfill are dealt with in Chapter 4. Both the copper canisters and the bentonite buffer play a key role in the repository by hindering groundwater from coming into contact with the nuclear fuel and ensuring that the radioactive substances are not dispersed to the surroundings. They must both fulfil their tasks as long as the fuel is dangerous, i.e. over 100,000 years. In the long-term the repository is affected by different processes, some of them are active over a short time while others are active over many tens of thousands of years. To capture this time span we have chosen to mention specific intervals in this chapter (from 10 years to 100,000 years) which are relevant for such processes. The points of departure for the time perspectives which are of immediate interest nearly all have in common that they begin when the canisters are deposited.

The possibility of gaining future experience from natural analogies is dealt with in Chapter 5. Natural analogies mean the occurrence of natural material and processes which can be expected in a repository. They can be seen as a long-term experiment in natural systems where a reactor zone may have been active for more than 100,000 years. The time perspective in this chapter covers millions of years.

Chapter 6, 'Geological Development', also addresses time spans of millions of years. Crystals which were formed more than 1,700 million years ago can be touched and studied today. Future climate change is an increasingly central question in the debate. The climate's future character is governed by interaction between astronomical factors which vary on a time scale of 10,000 to 100,000 years and changes in the concentration of carbon dioxide in the atmosphere which occur on a time scale of 100 to a few thousand years and which are caused by man and/or by nature.

Figure 1.1 on the following page – for lack of space a logarithmic scale is used – illustrates the entire time perspective covered by the different contributions.

Figure 1.1 Time perspective for nuclear waste



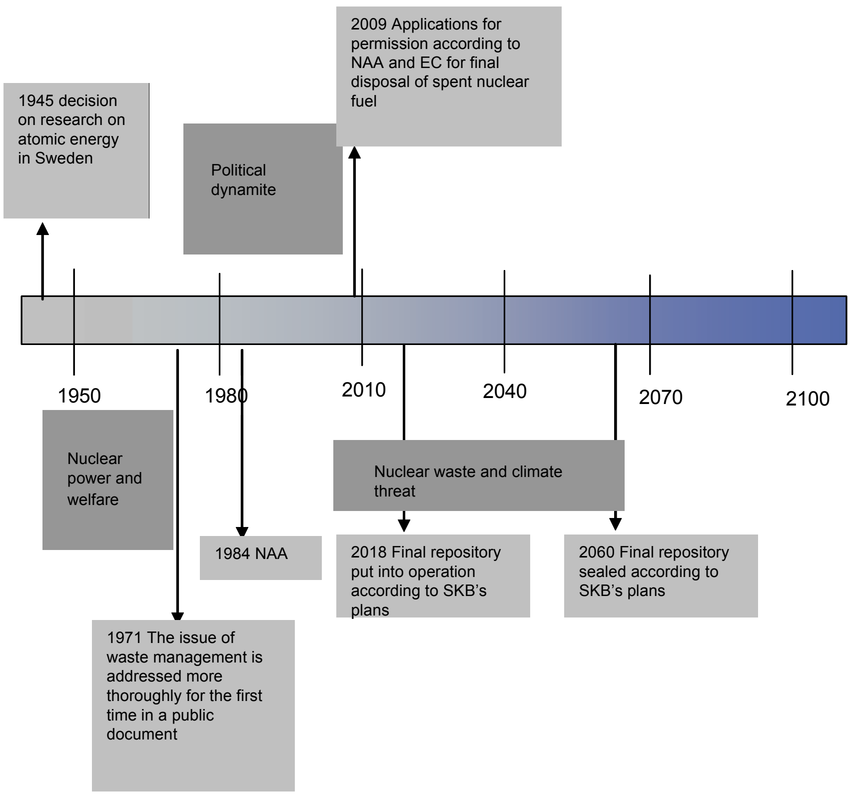
2 The nuclear waste issue and the development of society in the post-war period – some perspectives

Lena Andersson-Skog and Olof Söderberg

In this chapter an account is given of some of the more important events which have taken place during the period of work concerned with the final disposal of spent nuclear fuel from Swedish nuclear power stations. An account is also given of the most important years in the planning process which the Swedish Nuclear Fuel and Waste Management Company (SKB) has designated for its further work. It should be emphasised here that this is a question of "the Company's" time schedule and that public institutions (Parliament, Government, State authorities, municipalities) have not taken a position on these plans. The development of these events should be viewed in the context of socio-economic development. One of the most prominent features in Swedish development has been the appearance of a, in many respects, unique political welfare programme financed by industrial expansion. A successful basic and engineering industry has been one of the prerequisites for this growth. The underlying prerequisite has been technical and scientific development which, since the end of the 19^{th} century has produced new material, better machines and more effective energy use.

Figure 2.1 illustrates a time perspective concerning the nuclear waste issue in Sweden.

Figure 2.1 Time perspective concerning the nuclear waste issue in Sweden



2.1 1945–1972: National mobilization for nuclear power and welfare

In the mid-19th century Sweden was a land characterized by agriculture, the export of raw materials and simple industrial production. The industrialisation process contributed to a change in Swedish society economically, politically and socially. By the middle of the 20th century Sweden was one of the world's richest countries following a century-long growth of GDP at an average rate of 2% per year.[1] Important driving forces in this development were the fast technical, industrial and organisational changes in

[1] Schön (2007).

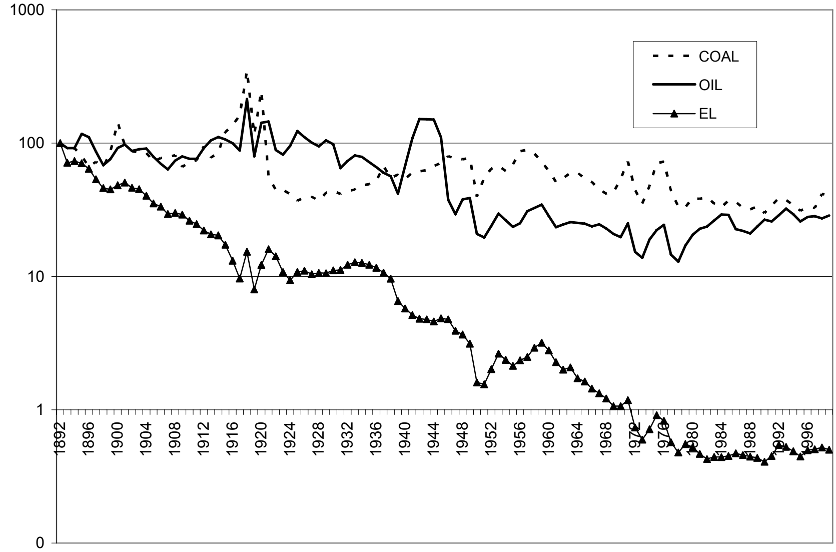
how goods and services were produced and distributed between different levels of society. A common picture is that manual labour and trades were replaced by machines and different types of physical infrastructure. These interconnected and technical changes are sometimes called development blocks since they constitute a basis for production conditions in society.[2] Transport and energy techniques are often considered to be a determining factor in this process of change since energy consumption increased nearly as much as capital investment. Industrialisation can be seen as a period when the use of energy, which had previously been based on wood and biomass, changed instead to oil, coal, hydropower and, in the post-war period, nuclear power.[3]

One of the important factors during the industrialisation period was the successful development of power techniques. Allmänna Svenska Elektriska Aktiebolaget (ASEA) specialised in electricity transmission and played a central role in the development of the Swedish energy industry and the transition to electricity within the processing and manufacturing industries. ASEA and Vattenfall – which at that time was a State-owned enterprise – became strong developers which fuelled progress in the development of electrification.

In figure 2.2 the relative price change between wood, oil and electricity during the period 1892–1999 is shown. It is clear that from the beginning of the 20th century there was a quick and continual decrease in the price of, above all, electric power in relation to the price of wood. It was only during the 1990s that the relative price reduction was checked and this coincided with the deregulation and internationalisation of the electricity markets.

[2] Dahmén (1950), Schön (2007).
[3] Wrigley (2004).

Figure 2.2 Prices of coal, oil and electricity relative to wood in Sweden 1892-1999 Index 1892 = 100



Source: Lindmark and Gustavsson-Bergqvist (2007).

Around 1950 electric power became a fundamental infrastructure both for the developing welfare of households and for industry's production conditions. This development went hand-in-hand with economic growth. In international economic historical research, the period between 1945 and 1970 is usually called "*the golden age: a period of strong increases in international welfare*". Sweden was one of the countries which benefited from increased wealth during this period. Initially the reconstruction of a razed Europe created a strong demand for Swedish raw materials such as wood, paper and steel, and this favoured Swedish growth. It was also a time of quick and radical change in Swedish society. It was only now that a really integrated Swedish national market for goods and services came about, a process strongly stimulated by the rationalization and heightened productivity within agriculture and industry.

At the same time urbanization created a concentration in those towns which remained in the rural areas and migration contributed to a growth of urban areas and large city suburbs. The other side of this was rapid migration from sparsely populated areas and forested provinces. During the 1950s real income also increased for most population groups. Consumption of capital goods rose thanks to an increase in real income for large groups of the population as household appliances made their way into Swedish homes and mass motorism made its breakthrough.

The development was partly a consequence of the economic policy which the Social Democratic Government had implemented concerning investment policy, employment, regional policies and social questions. What is today usually called the Swedish model also came about during the 1960s and 1970s.[4] This economic policy focussed on national expansion and an increased ambition level in matters of health and medical care, childcare and schools and, at the same time, investment in social benefits such as child benefit, national insurance, housing allowance, etc. It was financed through the increased tax revenue which the economic growth provided. It is clear that the Social Democratic Party saw industrial development as society's engine of change.[5] This development meant that there was a constant demand for increased energy for industry and households. At an early stage, hydropower in Sweden had become the domestic energy resource developed at national level. As early as the 1940s discussions had taken place on how the future energy need should be met and a rapidly growing import of oil was considered necessary to provide the electricity demanded by industry and households.

Besides hydropower there was another domestic energy source, considerable uranium deposits.[6] With this energy reserve as a potential base, nuclear power was seen as a complement and/or alternative to oil import and hydroelectricity. Even if the domestic uranium deposits have not been used on a large scale up until now, since 1975 an ever increasing part of the electricity has been produced by nuclear power stations, see table 2.1

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[4] Magnusson (1996).
[5] Andersson (2003), Friman (2002).
[6] Andersson-Skog (2005).

Table 2.1 Domestic net production of electric power (TWh) by means of production (%) 1970 to 2000

Production means	1970	1975	1980	1985	1990	1995	2000
Net production (TWh)	59.1	78.6	94.0	132.3	141.7	144.1	141.8
Import minus export (TWh)	4.3	1.3	0.5	-1.5	-1.8	-1.7	4.7
Hydropower (%)	69.0	72.5	61.7	52.8	50.4	46.7	54.9
Nuclear power (%)	-	14.5	26.9	42.2	46.0	46.5	38.6
Heat & power in industry (%)	5.2	4.2	4.2	1.8	1.9	2.7	3.0
Heat & power in district heating systems (%)	4.3	4.2	5.9	2.8	1.7	4.1	3.2
Condense power (%)	20.3	4.4	1.1	0.4	0.0	0.0	0.0
Gas turbines (%)	1.1	0.1	0.2	0.0	0.0	0.0	0.0
Wind power (%)	-	-	-	0.0	0.0	0.0	0.3

Source: Revised from Andersson-Skog (2005).

Already in 1945 the Swedish State, in cooperation with trade and industry, decided to begin research on what was then called "atomic power" or "atomic energy". This was a venture in which political motives for research as well as for industry were merged in the hope that the result would be of both military and civil use. The enterprise was carried on within the framework of AB Atomenergi which had been founded in 1947 and which was 57% State-owned with the remaining part being owned by Swedish municipal and private power companies as well as industrial companies.

Nuclear power reactors for heat and electricity production had been developed in the USA, the United Kingdom and the Soviet Union at the beginning of the 1950s. Certain constructions were intended as much for electricity and heat production as for the manufacture of plutonium for weapons.

The first research reactor in Sweden was built at the Royal Institute of Technology, located in its premises in Stockholm and was put into operation in 1954 and closed in 1970. A second research reactor was located some years later at Studsvik (north of

Nyköping) which, from the mid-1950s, became a Swedish nuclear technical research centre.[7]

During the first decade of "the atomic energy programme" there was no public debate in Sweden on how to manage high-level waste generated by this programme.

1956 is seen as an important year for the development of atomic power for civil purposes in Sweden. Of utmost importance was the fact that, at the United Nations Conference in Geneva in 1955 on the peaceful development of nuclear power, there had been strong optimism about the possibility of the efficient and economic use of nuclear energy. This was caused *inter alia* by the fact that the USA had declared at the Conference that it was ready to give other countries access to previously secret technical information. Another important point was that the USA had indicated the possibility of selling enrichment services for use in power reactors.

On the basis of proposals from several different enquiries, in 1956 Parliament decided on a programme and a regulatory framework in the field of atomic energy.[8] The programme stated, *inter alia*, that AB Atomenergi should have decisive influence on the construction work and that this should be aimed at the use of natural uranium with heavy water as a moderator. The programme ("the Swedish line") also included domestic fuel provision and reprocessing of spent fuel.[9] The regulatory framework was first expressed in a new Act (1956:306) on the right to extract atomic energy etc. (Atomic Energy Act). The Act contained provisions on the

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[7] This research reactor was put into operation in 1960 and was in use up until 2005. A second research reactor in Studsvik was also in use from 1960 to 2005. A decision has been made to dismantle both these reactors. The fuel from the research reactors in Studsvik will be returned to the Department of Energy in the USA in 2007 and the reactor components with high induction activity will be dismantled within a few years and stored within the Studsvik plant pending final disposal. The research reactor at the Royal Institute of Technology has been dismantled and all radioactivity has been removed from the site where the reactor was located. Since 1985 the site can be used for other activities.

[8] Cf. prop. 1956:176 regarding guidelines for development work in the field of atomic energy 3LU 22 respectively prop. 1956:178 with a proposal for a law on the right to extract atomic energy, etc. 3LU 23.

[9] During the preceding investigative work plans had been drafted to build about five nuclear heat reactors before 1965 and some nuclear power reactors before 1970. Of these only the heat producing reactor in Ågesta was built. In 1958 Parliament approved plans to locate a nuclear power reactor at Marviken (north of Norrköping). Construction started in 1964 but the work stopped in 1969 when it became clear that it would be necessary to restructure important safety systems. Since technical development had made the heavy water approach unfeasible, the cost of restructuring was considered to be too high and the plant was dismantled.

requirements for permission to build, possess or operate atomic reactors and the plants for the processing of atomic fuel.

The Government Bill on guidelines for development work in the field of atomic energy contains certain information on the danger of waste (prop. 1956: 176 pp. 5 and 19). However this information is to be found in the report of the underlying enquiry and is not mentioned in the part of the Bill where the Government's proposal is reported (pp. 34-43). Nor during the Committee reading of the Bill does the question of the danger of waste seem to have raised special interest (cf. 3 LU 1956.22).

The first time that the question of waste drew public attention in Sweden was probably at the beginning of the 1960s. At that time plans were in progress for what became the heat producing reactor in Ågesta[10] (which from 1964 to 1974 provided the southern part of Greater Stockholm with heat). The residents in the surrounding area mistrusted the assurances of the atomic experts that certain low-intensity emissions of radioactive rest products were not dangerous. However the protest was, to a large extent of a local nature and never developed to a more principled discussion on the issue of waste.[11]

1966 can be seen as a milestone in the development of the Swedish atomic energy programme. Since the end of the 1950s private power producers as well as electricity-intensive industry, such as the then Statens vattenfallsverk, had, for different reasons, become interested in a completely different concept for reactors in electricity production, namely light water reactors. In 1959 a forerunner to today's OKG AB applied for a concession from the Government for a small light water reactor which would be located on the Simpevarp peninsula north of Oskarshamn. The plans for the project changed however and in 1965 the company applied for a concession for the reactor which was to become the first nuclear power reactor in Sweden (O 1). It became commercially operational in 1972.

During the 1960s there was an ongoing debate among both nuclear power experts and in a public context concerning security

[10] The Ågesta reactor provided the southern part of Greater Stockholm with heat from 1964 to 1974. Spent nuclear fuel and high-level nuclear waste were transported from the plant to Studsvik where it is still deposited. It is intended to dismantle the reactor when a place has been identified to which the dismantled waste from today's nuclear power reactors can be transported.

[11] Anshelm (2006) **pp. 25-26.**

and economy in the Marviken project[12] and on the choice of “the Swedish line” i.e. heavy water reactors. In 1966 the Government launched a new atomic energy enquiry to review the organisation and financing of the industrial development work concerning nuclear power. This development work was increasingly aimed towards economic policy for which the Ministry of Industry, which was established some years later, functioned as an important actor. The result was that from 1968 large parts of AB Atomenergi merged with parts of privately-owned ASEA to become a semi State-owned company, Asea-Atom, and its main task was to build nuclear power reactors.[13] During 1969-1972 the owners of the prospective nuclear power stations in Oskarshamn, Ringhals, Barsebäck and Forsmark ordered seven more light water reactors, most of them from Asea-Atom. Parliament took part in this expansion only to the degree necessary to provide investment funds for such projects in which Statens vattenfallsverk was engaged. No political party questioned the expansion. Nor was the question of nuclear waste raised by any political party before 1972.

Many people during that period have testified that the question of how nuclear waste from the new nuclear power reactors should be managed was practically a “non-issue”. On questions from the general public in the regions where nuclear power stations were to be located, industry representatives assured them that there was no reason for concern and that any question would have a solution.

It should be emphasised here, that up until the 1980s, experts within the nuclear power industry had assumed that the spent nuclear fuel from the Swedish reactors would be reprocessed and possibly, to a large extent, reused in specific reactors. Spent nuclear fuel was, therefore, not seen as waste but primarily as a resource. It was considered to be the high-level waste products from the reprocessing which would require long-term disposal. The volume of this waste was said to be proportionately small.[14]

In the years around 1970 however – and influenced by a discussion which had originated in the USA – public debate was directed to the nuclear waste issue. The debate on this issue played a decisive part in the political energy debate on the role of nuclear power

[12] See footnote 9 concerning this project.
[13] Leijonhufvud (1994).
[14] It was only at the beginning of the 1980s that it became clear in Sweden that the aim would be to finally dispose of the spent fuel without previous reprocessing. See below.

which started about this time and which, in large part, has characterised Swedish domestic policy up until now. A debate on nuclear power which was carried in the daily newspaper Dagens Nyheter in the spring of 1970 can be seen as an introductory first challenge of what would later be called atomic euphoria and technical optimism.[15]

The first time the question of waste management was dealt with in a more in-depth way in a public document was in 1971. The document was published by the Ministry of Industry under the title "*Upparbetning av använt kärnbränsle*" (Reprocessing of spent nuclear fuel).[16] It was the result of a study carried out by a working group of officials from different ministries which, in April 1970, had been given the additional task of investigating the conditions for a Swedish reprocessing plant. The background for the document was that the State had bought a piece of land in Sannäs in Bohuslän. It was judged that this area would be a feasible site for a Swedish reprocessing plant as well as a place for the final disposal of waste from such a plant. The plans were met with strong local opposition in 1969 and at the beginning of 1970. In the study, dated March 1971, it was reported that it would be possible to reprocess the spent nuclear fuel abroad but that the responsibility for the waste from the reprocessing must lie with the country of origin. That there were methods for the safe final disposal of reprocessing waste was not questioned in the working group's report.[17]

There were, however, at least within one political party, the Centre Party, some people who began to doubt the ability of technicians and scientists to deal with the nuclear waste issue. This doubt was expressed in a minor addition to a proposal for the party programme which the party board had put forward at the Party Congress in Gothenburg in March 1970. This addition, however did not lead to any immediate change of course in the still clearly positive attitude to nuclear power which the Centre Party demonstrated in the Riksdag in 1971. A total change of direction came only in 1972.

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[15] The expressions are used by **Anshelm (2006) p.17.**

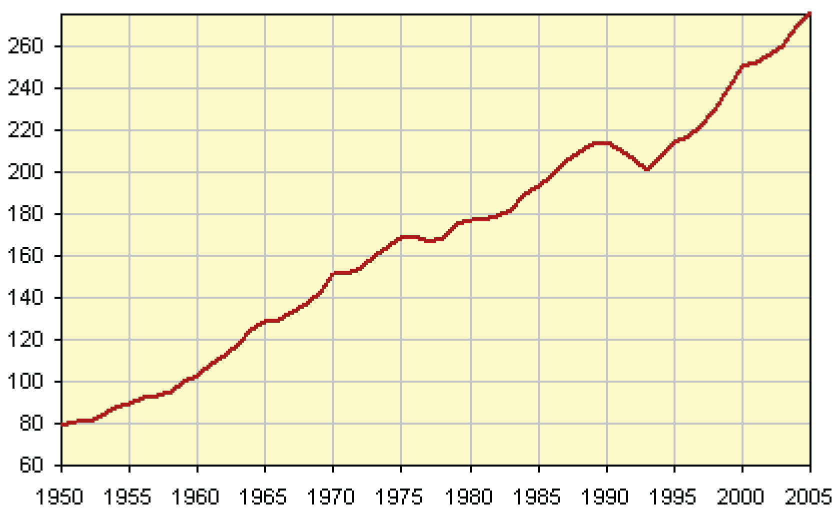
[16] Ds I 1971:I.

[17] AB Atomenergi had worked with the reprocessing technique during the late 1960s. It can also be said that in 1969 OKG signed an agreement with the State-owned British Nuclear Fuel Limited (BNLF) concerning the reprocessing of spent nuclear fuel in which it was taken for granted that the high-level waste would finally be deposited in the United Kingdom after reprocessing.

2.2 1972–2006: Political dynamite – nuclear waste, economy and environmental mobilization

The change in the view on nuclear power coincided – perhaps somewhat paradoxically – with the international structural crisis which had been noticeable since the end of the 1960s and which led to the world economic crisis in 1973–1976. Central to this crisis were the basic industries – mining, steel, shipyards – and energy supply. Both 1973 and 1976 were characterised by the oil crisis which meant that the price of oil increased sharply. For the processing industries the rising energy prices also meant a sharp increase in the price of consumer goods. Inflation and unemployment created major problems. Economic expansion slowed considerably and the growth of GNP fell from its previously high rate. Growth was even negative for some years, see figure 2.3.

Figure 2.3 Gross National Product (GNP) per capita 1950–2005
Thousand Kronor, fixed prices, price level for year 2000



Source: SCB. Data up to and including 2005.

In Sweden the problem was evident as much in the mining industry as in the steel and shipbuilding industries. Unemployment increased in certain sectors and regions to inter-war levels.[18] The

[18] Olofson (2002).

provinces in Norrland were particularly affected and different regional and labour market policies were put in place to ease the situation. It was, however, not only the basic industries which were affected. During this time large parts of Sweden's consumer goods production were wiped out when the textile and shoe industries, for example, closed down and moved to low income countries in Europe.[19] However, this did not stop investment in public welfare solutions. During the 1970s Sweden took decisive steps towards a more equal society by introducing laws on family rights and equality and, in the labour market, LAS (Employment Protection Act) and MBL (Act on the Joint Regulation of Working Life).

At this time there was increased ideological opposition to large-scale investment and growth which had characterised the change in society during the 20th century. Small-scale, decentralisation and joint decision-making were the trends which were advocated both in the Green movement and in parts of the Left movement, both of which had been active since the mid-1960s. Despite the large difference between these social movements, they both demanded an alternative economic agenda.

Instead, however, the Swedish economy became internationalised to a higher degree during the 1980s. An international period of economic recovery during the 1980s, as well as a devaluation of the Swedish currency in 1982 contributed to the fact that profitability in the energy-intensive export industry increased. At the same time there was a change towards more service-oriented and knowledge-intensive production. There were also important changes in Swedish economic policy during the 1980s. The credit market was deregulated, the tax system reformed and one of the cornerstones in the Swedish model, the solidarity-based wage policy, was scrapped. At the same time so-called deregulation of the earlier politically controlled branches within the transport and the communication sectors took place. This deregulation interacted with growing international trade. In Europe, society and the economy were also affected by the expansion of the European Union and the political dissolution of the so-called Eastern Bloc in 1989.

This fact rewrote the map concerning ownership, international enterprise and development of the Swedish economy. One example is that Swedish direct investment increased sharply during the second half of the 1980s.[20] This picture changed at the beginning of

[19] Gråbacke (2002).
[20] **Schön p.418.**

the 1990s, especially after a depreciation in the value of the Swedish krona in autumn 1992. The inflow of foreign capital increased during the 1990s and international mergers and the takeover of Swedish companies meant that large parts of the export companies lost their Swedish base. One example is Asea-Atom which merged with the Swiss firm Brown-Boveri in 1988 to become ABB.[21]

Cross ownership within the electric power industry has long existed in State-owned as well as private spheres. Some examples can be given here. The Swedish State had already, with the establishment of Vattenfall around the turn of the century in 1900, been a dominant actor within Swedish electric power generation and, as such, had instigated the development of technical power during the 20th century.[22] Vattenfall mainly distributed electricity to industry: from an early date SJ (State railways), the mining-, steel-, and forest-industry were important customers. In addition, the private electricity industry expanded at the beginning of the 1900s and already in 1915 the regional Danish and Swedish electricity distribution grids were connected by the Öresund cable. Sydsvenska kraftaktiebolaget was established in 1906 and changed its name to Sydkraft in 1977. During the post-war years the company acquired several regional power companies, among others, Graningeverken and Örebro energy. With Sweden's entry into the European Union in 1995 and with the European Union directive on free trade in the electricity market, competition was introduced into the Swedish electricity market in 1996. This meant that the electricity customers could now choose their distributor. Business opportunities for electricity producers also changed. For example, since 1997 Vattenfall has entered mainly the Nordic, German and Polish electricity markets. In 2001 Sydkraft was bought by the German E.ON-group. Its work in Sweden is carried on within the framework of E.ON Sverige AB and the Norwegian company Statkraft is a major minority owner. International ownership of power production in different countries means that national electricity prices today are far from being decided by production costs in their respective countries. Instead, international demand for electric energy, together with national tax rates, will be the driving force for price development. Different environmental considerations will

[21] The company was bought in 2000 by British Nuclear Fuel Ltd. (BNFL) and is now called Westinghouse Electric Sweden AB.
[22] Jörnmark (2004).

also play an increasing role in national decisions on the use of energy and its different effects on the environment.

Since the 1992 United Nations Conference on Environment and Development in Rio, the expression *sustainable development* has had a more powerful impact. In the beginning it was an expression of a political vision but gradually it was understood as a real necessity. The expansive global economic processes of the 1980s were, from the mid-1990s, accompanied by a growing global, social and ecological counter- movement. Within this counter-movement the long-term threat to the survival of mankind was interpreted in terms of energy use. This clearly affected attitudes towards nuclear waste.

The development of the nuclear waste issue which took place over some 30 years can be divided into four rather clear periods: 1972–1978, 1979–1984, 1985–1992 and 1992–2006.

1972–1978

Quite suddenly during the period 1972–1978, the question of how to manage spent nuclear fuel became a central political point of issue of such dimension that it strongly contributed to two changes in Government (the Social Democrats election loss and the split of the non-socialist Government which took office in 1978 after the election). The nuclear power industry initiated the Nuclear Fuel Safety Project (KBS) (Kärnbränslesäkerhet) for the purpose of effecting the safe final disposal of the high-level waste from the nuclear power stations. The project was aimed at a method for the final disposal of, primarily, waste from the reprocessed nuclear fuel.

One of the most renowned critics of the nuclear power programme in Sweden was the Nobel Prize laureate in Physics, Hannes Alfvén. In a lecture in the summer of 1972 at an alternative parallel conference (the People's Forum) to the United Nations Conference on the Human Environment in Stockholm, he maintained, *inter alia*, that there was no acceptable method available to deal with the radioactive waste from nuclear power.

Within the Centre Party's parliamentary group, Birgitta Hambraeus had become interested in nuclear power issues and in 1972 she grew increasingly sceptical about such matters, not least after contact with Alfvén and nuclear power critics from the USA connected with the United Nations Conference on the Human Environment. She felt that the answers which she received from different experts on the issue of waste management were far from satisfactory and that advocates of nuclear power did not pay the waste issue sufficient attention. In October 1972, in an interpellation in Parliament, she raised the question of high-level nuclear waste and requested that the Minister of Industry (Rune Johansson) should clarify the Government's position. She asked if it were morally justifiable "to produce substances which must be monitored and managed with technically complicated methods by coming generations in the unforeseeable future". She also asked if the increased quantities of high-level waste from the nuclear power stations constituted a sufficiently large problem for the Government to submit the question of the continued expansion of nuclear power to Parliament for consideration. Her interpellation was the first time the question of an expansion of nuclear power had been raised in Parliament and, in fact, with the waste problem as the most important argument.[23]

It should be remembered here that the waste which Birgitta Hambraeus had foremost in mind was waste from reprocessing of the spent nuclear fuel. The alternative of direct disposal of spent nuclear fuel was not a topic of interest at this time.

In his reply to her interpellation at the end of November 1972, the Minister of Industry said that the problem of waste did not give rise to any reconsideration of the Swedish nuclear power programme. This answer was also an admission that, at that point, there was no internationally accepted final solution to the problem of waste. However the Minister reckoned "entirely satisfactory methods" would be available in the future when the final disposal of the waste had to be addressed. He also announced that a joint parliamentary committee on the nuclear waste question would be appointed.

An enquiry "concerning high-level waste from nuclear power stations", the so-called AKA enquiry, was initiated some months later. This work laid the foundation for a programme to manage waste from the Swedish nuclear power stations. The Committee worked against a background of increased shaping of public opinion on the questions of nuclear power and nuclear waste and a

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[23] Vedung (2005).

simultaneous politicising of the questions. Some important steps in this political course of events were the following.

In the 1973 Budget Bill the Government announced its plans for such an expansion of Swedish nuclear power production that it would, by 1985, account for half of the Swedish electricity production. In a motion, Birgitta Hambraeus stressed the risk in connection with waste management. She requested a ban on further expansion of production if Parliament's enquiry showed that the expansion programme would bring about unacceptable risks from a safety or environmental point of view. The motion was referred to the Committee on Industry and Trade which arranged a hearing with experts and researchers, among others, Hannes Alfvén. The Committee did indeed oppose the motion and it was rejected by Parliament. However, at the same time, on a further proposal from the Committee, Parliament expressed that "in its opinion" no decision on the further extension of nuclear power "should be made before a new, comprehensive decision basis comprising, *inter alia*, information on the results of the research and development trends, has been placed before Parliament" (NU 1973:49 p.19). The Centre Party and the Left Party reserved their positions in favour of more restrictive language concerning nuclear power and, with that, they introduced for the first time in Parliament a lasting political controversy concerning nuclear power policy, *inter alia*, with reference to the problem of waste.[24]

The statement from Parliament just referred to can be interpreted as a growing understanding that, henceforth, more attention should be paid to the problems of nuclear waste than had been the case up until then. The waste issue was no longer a matter for only experts and the highest political decision-makers but had become part of public debate. Nor at this time did the minority within Parliament which was critical to nuclear power go so far as to demand its phasing-out.

In the spring of 1975 the Government proposed guidelines in the field of energy policies. They implied, *inter alia*, "a continued cautious expansion of nuclear power" with two reactors over and above the eleven which until then had been decided on. A majority

[24] According to a declaration by the present non-socialist Government on 6 October 2006, it will not take any political decision during the period of its mandate 2006-2010 on the phasing-out of nuclear power reactors. In December 2006 representatives of the Left Party and the Green Party spoke of a phasing-out of nuclear power until 2025 and within 12 years, respectively (Committee on Industry and Trade report 2006/07: NU3).

in Parliament supported the guidelines but the opposition between the Centre Party and the Left Party on one side and the remaining political parties on the other had now become more pronounced. The motivation for the opposition of the two political parties critical to nuclear power was said to be the problem of waste but the emphasis was on the risks in connection with the operation of the nuclear power stations and the risk of contributing to the proliferation of nuclear weapons (NU 1975:30).

The results of AKA's enquiry were submitted in spring 1976.[25] The Committee proposed, *inter alia*, that the spent nuclear fuel be deposited in a central storage facility pending reprocessing and that preparatory work should be initiated to build a Swedish reprocessing plant and a final repository plant in the crystalline bedrock for the high-level waste after reprocessing. Investigations on the feasibility of the bedrock should be carried out near the nuclear power stations in Forsmark and Simpevarp and at "alternative sites". Even if the Committee had initially prescribed reprocessing of the spent nuclear fuel, it was of the opinion that the study should also better clarify the conditions for direct disposal of the fuel. The Committee also pointed out possible solutions to the question of final disposal of low- and intermediate-level waste from nuclear technical activities.

The AKA Committee also raised the question of organisation and financing of the work in connection with rest products from nuclear power. The Committee took as a point of departure that the responsibility for dealing with radioactive waste primarily rests with the company or the institution where the waste originated. In the Terms of Reference for the Committee work which the Government had drawn up it is stated "that it shall be the responsibility of the State to deal with the activities concerning final disposal of high-level waste".[26] The Committee proposed that a special governmental organisation be established for "all long-term management of radioactive waste and work elements associated with it". A specific committee on organisation should be appointed to further specify these tasks. The Committee was also of the opinion that the Swedish Nuclear Fuel and Waste Management Company (SKBF) (Svensk Kärnbränsleförsörjning AB) which was founded in 1973 by the nuclear power industry for the joint

[25] Spent nuclear fuel and radioactive waste – report of the AKA Committee, SOU 1976: 30-31 and 41 (Swedish Government Official Reports).
[26] The Terms of Reference are reproduced in **SOU 1976:31 pp.187-192.**

purchase of fuel[27] would have a central role in the continued research and planning work of the waste management question. The cost for all the essential measures should, according to the enquiry, be borne by those who produced the waste, i.e. in practice primarily the nuclear power industry. It should be forced to include future estimated costs for waste management in its cost calculations and each year set aside funds in its budget to cover such costs. However, at the same time the Committee pointed out an alternative form of financing, namely that the State put a special charge on the electric energy delivered from the nuclear power stations and at the same time accept to cover the costs.[28]

The question of nuclear waste and the expansion of nuclear power was one of the main issues during the 1976 election campaign. The leader of the Centre Party, Torbjörn Fälldin, maintained in television debates with the then Prime Minister, Olof Palme, that the AKA enquiry showed that the waste problem could not be solved, while Palme was of the opinion that the enquiry showed possible solutions on every point.[29] Surveys done after the election showed that the nuclear power question had strongly contributed to the Social Democrats loss in the election. The non-socialist Government which, under the leadership of Torbjörn Fälldin, had taken office after the election, included political parties with strongly diverging views on the nuclear power issue. For the sake of unity, they were forced to find a compromise. In the Government's statement they announced that certain conditions should be put in place for the nuclear power industry to be allowed to put into operation the nuclear power reactors which were then under construction. Furthermore, a special commission would be appointed to provide a basis for a new decision on energy policy, *inter alia*, concerning the role of nuclear power.

The so-called Stipulations Act (1977:140) (Villkorslagen) entered into force in May 1977. The main provision of the Act was aimed at nuclear power reactors which had been built but which had not yet received final permission to operate. To receive such permission from the Government the reactors owner had to fulfil one of two conditions. One was that he have a contract which in an

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[27] According to the agreement regarding SKBF the Chairman of the Board should be appointed by the Government. In practice this task was to be entrusted to the State Secretary in the Ministry of Industry. Thus the company enjoyed a special relationship with the Government machinery.

[28] **SOU 1976: 30 pp. 95-97.**

[29] **Anshelm (2006) pp.63-64.**

"absolutely safe" way provides for the need of reprocessing of spent nuclear fuel. The other alternative was that the reactor owner could show how and where an "absolutely safe" final disposal of spent, unreprocessed, nuclear fuel could take place.

The joint parliamentary so-called Energy Commission (Energikommissionen) put forward its main considerations in February 1978.[30] A majority within the Commission recommended that the ongoing nuclear power expansion should proceed but be limited to a maximum of eleven reactors.

The new Government was negatively inclined to the idea that the State, as the AKA Committee proposed, should be engaged in the issue of waste management. The responsibility for this should clearly lie with the power industry. An earlier arrangement that the State Secretary in the Ministry of Industry be Chairman in SKBF was discontinued. Instead the chairmanship of the company was taken over by Vattenfall in its capacity as largest partner. The Company's work was now aimed nearly entirely at the issue of waste management and the partners placed economic resources at its disposal. The so-called Nuclear Fuel Safety Project KBS (Projekt Kärnbränslesäkerhet) was started in autumn 1976 and in November 1977 it presented a report (KBS-1) which treated safety at final disposal of vitrified reprocessing material. This report laid the ground for the Government's first considerations in 1978 concerning permission to operate according to the Stipulations Act.

The controversies concerning the nuclear power issue within the Government, which also included different opinions on the interpretation of the Stipulations Act's provision on "absolutely safe" final disposal – led to the resignation of the Government in 1978. It was succeeded by a Liberal Party minority Government which held office until the elections in autumn 1979.

The outgoing Government had not taken a position on the issues of organisation and financing which the AKA Committee had brought to the fore. At the end of 1978 the new Government appointed an investigator with the task of proposing a solution to these issues.[31]

Already during the work of the AKA Committee – and at its proposal – a smaller organisation, Programrådet för radioaktivt avfall (PRAV), was created. PRAV had a formal attachment to the

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[30] SOU 1978:17.

[31] In 1980 the investigator submitted a report called 'Waste from Nuclear Power – Organisation and Financing' (SOU 1980:14).

Ministry of Industry but its work, which comprised geological investigations including test drillings – was financed principally by the power industries via SKBF.[32]

Within the industry the KBS project continued and in 1978 resulted in the KBS-2 report which dealt with the possibilities of direct disposal of the spent nuclear fuel.

1979–1984

One determining factor in the political handling of the nuclear power issue during this period was the Harrisburg accident in March 1979 and the following advisory referendum on nuclear power in Sweden in spring 1980. 2010 was set as the end point for nuclear power. From a waste perspective the decision on the year 2010 meant that it was possible to judge with greater certainty the volume of different types of nuclear waste which would have to be managed. At the beginning of the 1980s the issue of reprocessing of the spent nuclear fuel became irrelevant from the Swedish point of view and work was aimed instead at the final disposal of spent nuclear fuel without preceding reprocessing so-called direct disposal. Construction was started on a plant for the final disposal of low- and intermediate-level nuclear waste, as well as construction of a central plant for intermediate disposal of the spent nuclear fuel. Geological investigations were started with a view to finding a site which was suitable for final disposal of the spent nuclear fuel, but in certain places these had to stop due to protests from demonstrating opponents. A financial system was created under Government auspices based on the proceeds received from charges levied on the production of nuclear power electricity. There was a clear division of responsibility between State and industry and this was given expression in the 1984 Nuclear Activities Act (Kärnteknik-lagen).

The reactor accident in Harrisburg in March 1979 led to the fact that the political parties agreed to postpone all decisions on the future of nuclear power until an advisory referendum had been arranged. The referendum was held in March 1980. When the result of the referendum became available the question was again taken up in national politics and in Parliament. A non-socialist Government (Fälldin II) had taken office after the 1979 election. A few

[32] PRAV's work stopped entirely in 1981 after which the geological investigations were successively taken over by SKBF.

weeks after the referendum the Government presented a Bill which contained a proposal for guidelines on energy policy. These guidelines included, *inter alia*, that a maximum of 12 reactors should be built and that these should be used during their technical lifespan which was judged to be 25 years from the date of initial operation. During the handling of the Government Bill by the Committee on Industry and Trade a further guideline was introduced on the grounds of a motion from the Social Democratic Party – that the last nuclear power reactor would be closed in 2010.

Even if the guidelines concerning nuclear power which Parliament had decided on were not explicitly formulated in legal text[33] in practice they were to govern activities related to waste issues for almost two decades. As previously mentioned, it now became possible to more or less calculate exactly the volume of the different types of waste which nuclear power production would give rise to, and on the basis of this information, future costs could be judged with increased certainty.

In the first years of the 1980s the work on the nuclear waste issue was characterised by the fact that the State and the power industry, influenced by international safety considerations as well as by micro-economic considerations, had developed a common view on how spent nuclear fuel should be dealt with. This common view meant that the spent nuclear fuel from the Swedish nuclear power stations would not be reprocessed. Instead research and development work was directed towards final disposal of the spent fuel, so-called direct disposal. SKBF, which had changed its name to the Swedish Nuclear Fuel and Waste Management Co. (SKB) (Svensk Kärnbränslehantering AB) in 1983 presented the KBS-3 report that same year. The report was a further development of the thoughts from KBS-2. The new report laid the foundation for an application to the Government – according to the provisions in the Stipulations Act – to be allowed to put the two last reactors in the Swedish nuclear power programme (Forsmark 3 and Oskarshamn 3) into operation. The application was granted in June 1984 under

[33] Later legislation has meant in fact that the restriction ”maximum 12” reactors has entered into law. This happened indirectly through the decision on a ban to build new nuclear power reactors which was introduced through an amendment in the Nuclear Activities Act 1986. Act (1977:320) on the phase-out of nuclear power should also be mentioned in this context since this Act gives the Government the authority to prescribe the closing of nuclear power reactors “as a consequence of a switch in the energy system in Sweden”. The Government decision on the closing of the two reactors in Barsebäck was made with reference to that Act.

the provisions of the new Nuclear Activities Act which had come into force in February 1984 (see below).

The geological investigations which PRAV had started at the end of the 1970s were, from the beginning of the 1980s, continued by SKBF, later SKB. These concerned deep drillings and measurements of the bedrock properties in some ten areas, later designated type-site investigations, in different parts of Sweden. In several places the investigations were met with protests from the local inhabitants and sometimes they had to be stopped. The best known example is perhaps Kynnefjäll in Bohuslän which, from 1980, and for a period of about 20 years, was uninterruptedly guarded by the local population.

An experimental study, which included international participants, took place under SKBF/SKB's management in the disused iron ore-mine in Stripa.

Parallel to industry's work with geological investigations and with the KBS-3 project, Government investigations dealt with the preparation of proposals for solutions to the organisational and financial questions. Most important was the work on a proposal for new legislation which would show clearly defined areas of responsibility for the nuclear industry and for the State in view of continued work on the nuclear waste issue.

The end result was two Acts which were of great importance for continued development.

Through Act (1981:669) on the financing of future costs of spent nuclear fuel, etc., a national financial system was created, the main features of which still remain today.[34] The principles behind this financial system can be summarized as follows:[35]

- The costs for the management of spent nuclear fuel and demolition of the nuclear technical plants shall be covered by the proceeds from the production of energy which has given rise to them. The costs will remain long after the nuclear power reactor has been closed. Therefore resources to finance future costs must continuously be taken from the proceeds from energy production and be safely kept to be gradually allocated for this purpose.

[34] The Act was replaced in 1992 by a new Act (1992:1537) with the same name and in 2006 by Act (2006:647) on financial measures for the management of rest products from nuclear technical work.
[35] Cf. prop. 1980/81:90 **annex 1 p. 319.**

- Anyone who carries out nuclear technical activities which give rise to nuclear waste must guarantee that this waste will be taken care of in a safe way. That means that companies, etc., not only must finance the necessary measures but also guarantee that the measures will, in fact, be taken.
- The State has overall responsibility for the radioactive waste. "The long-term responsibility for the management and final disposal should lie with the State. The responsibility for the work should consequently be shared between the power companies and the State…."

A further Act (1984:3) on nuclear technology safety was passed and is still valid today. The proposal for the Act had been prepared by a joint parliamentary committee which had been appointed in 1979, the so-called Atomlagstiftningskommittéen (Committee on Atomic Energy Legislation). The Act clearly establishes the reactor owner's responsibility for, *inter alia,* waste management. It is clear that this responsibility also includes responsibility for carrying out all necessary measures to finance this. It is interesting to note that the new Act requires "safe" final disposal (the wording in the Stipulations Act "absolutely safe" has consequently disappeared from the legal text) and also that the reactor owners – in practice SKB – shall present a programme for the continued research and development work on the nuclear waste issue every third year and that this programme shall be reviewed by different authorities and finally approved by the Government. According to the new Act the first of these programmes should have been submitted in 1986, which it was.

The Act also contains definitions of the notion of "nuclear material" and "nuclear waste". According to this definition, spent nuclear fuel constitutes "nuclear waste" only when it has been placed in a final repository – before then it is defined as "nuclear material". It should also be stressed that the Nuclear Activities Act does not contain any provision which prescribes direct disposal of the spent nuclear fuel. Consequently the Act also leaves open the possibility of final disposal of waste after reprocessing of the spent nuclear fuel, even if the representatives of both State and industry presently find this unsuitable.

As already mentioned, the nuclear power industry presented the KBS-3 report on direct disposal of spent nuclear fuel in Swedish bedrock in 1983. The Government decision in June 1984 that reactors F3 and O3 be allowed to be put into operation was based, *inter alia*, on the content of that report, as well as on a document called R&D programme 84 (FoU Program 84), which SKB had prepared and which was reviewed by the two most concerned authorities – the Swedish Nuclear Power Inspectorate (SKI) and the Swedish Radiation Protection Authority (SSI).

1985–1992

On the basis of the 1984 Nuclear Activities Act a partly new Government organisation was created during this period. SKB discontinued geological investigations in the field and instead changed to the study of the country's geology on the basis of available map material, etc. A central interim storage facility for spent nuclear fuel (CLAB) started up. SKB compiled two further R&D programmes (1986 and 1989). In these programmes, which were reviewed by supervisory authorities and approved by the Government, it presented the plan for a bedrock laboratory in Äspö (near the nuclear power plant in Oskarshamn). It further developed the KBS-3 method and highlighted alternative disposal methods.

In 1985 a partly new State authority structure was introduced on nuclear waste issues. SKI and SSI would, as previously, be responsible for safety and radiation protection questions and grant permission for the necessary nuclear technical work (to the extent that it was not the Government which granted the permission). A new authority, the National Board for Spent Nuclear Fuel (SKN) (Statens kärnbränslenämnd), was given the task of administering the financial system[36] and examining the R&D programme concerning the waste management issue which industry henceforth should submit every third year. A national council for the issue of nuclear waste (KASAM) would see to the exchange of information between SKI, SSI and SKN on the question of their research work on the waste management issue, as well as annually providing the Government with a review of the state-of-the-art in the field of

[36] The task of administering the financial system had, up until then, been with Nämnden för hantering av använt kärnbränsle (NAK) (National Board for the Management of Spent Nuclear Fuel). Within the framework of that authority it had also followed industry's research and development work on the issue of nuclear waste as well as initiating certain further work.

nuclear waste. In 1990 KASAM was reorganised to become a scientific council under SKN.

As already mentioned, the geological investigations carried out by SKB throughout different parts of the country during the first part of the 1980s met with growing opposition among the inhabitants of surrounding areas. When SKB, shortly after the Parliamentary election in September 1985, intended to carry out drillings in the vicinity of Almunge (Uppsala municipality) there were extensive protests and the work place was blocked by residents. A reorientation of the work was necessary.

In the summer of 1985 SKB presented the first completed central interim storage facility in the world for the storage of spent nuclear fuel, CLAB in Oskarshamn. The plant was large enough for the volume which the Swedish nuclear power programme was estimated to require and meant that the storage problem could be considered solved for the next 40-60 years.[37] Therefore there was little urgency to find a site for final disposal of the spent nuclear fuel.

The studies of the geological conditions in Sweden in the coming years were based entirely on material which had already been produced by the Geological Survey of Sweden (SGU) and which was publicly available.[38] Consequently no field studies took place. Parallel to this, in 1986 and 1989, R&D Programmes were prepared which were examined by supervisory authorities and approved by the Government. In these programmes plans were announced to build the Äspö laboratory immediately adjacent to the Oskarshamn plant. SKB further developed the KBS-3 method and – at the request of the authorities and the Government – highlighted alternative methods and solutions for the final disposal of spent nuclear fuel in the bedrock.

1992–2006

From 1992 until today SKB has carried out a site selection process which has been built on the voluntary participation of a number of municipalities where so-called feasibility studies were carried out during the 1990s. From the conclusions of these feasibility studies, including consideration of the opinions related to SKBs work within

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[37] It was assumed that spent fuel, after it was taken out of the reactor and transported to CLAB, would need to lie there for around 40 years before the cooling-off and radioactivity would allow encapsulation before final disposal.

[38] The results of these studies were first reported by SKB in 1995 in a so-called overview study.

the concerned municipalities, SKB site choice investigations started in two places in 2002, in the municipalities of Oskarshamn and Östhammar. On a total of seven occasions (1992, 1994, 1995, 1998, 2000, 2001 and 2004) SKB presented the RD&D (Research, Development and Demonstration) programmes (including requested supplements), which have been reviewed by the supervisory authorities and others and approved by the Government. The application which SKB submitted to SKI in November 2006 for a permit to build an encapsulation plant for spent nuclear fuel according to the Nuclear Activities Act, constitutes a natural end point for this period.

A new phase in the work of SKB started in 1992. It was understood that work with the geological overview studies showed that there were many areas in Sweden which, from a geological point of view, could be suitable for a final repository for spent nuclear fuel. The Company wanted, therefore, to contact municipalities which were interested in cooperating in the work to further study the conditions for the placement of such a repository. In the so-called RD&D programme 92, SKB had drafted a concrete plan on how to implement the construction of a repository for the spent fuel. Some months later – at the end of 1992 – SKB sent a letter to all municipalities in the country and invited them to cooperate in so-called feasibility studies.

After several setbacks, detailed elsewhere, the end results were as follows:[39]

- feasibility studies were carried out in eight different municipalities
- two of these municipalities held municipal referendums after which further work was discontinued (Storuman and Malå).

[39] See for example Förstudiekommuner i dialog med allmänheten: examplen Nyköping, Oskarshamn, och Tierp (KASAM:s rapport Kunskapsläget på kärnavfallsområdet 2001, SOU 2001:35 p..15–42), Feasibility study on municipalities in dialogue with the general public: example Nyköping, Oskarshamn and Tierp (KASAM's report State-of-the-art in the field of nuclear waste), Plats för slutförvaring av kärnavfall – förstudier i åtta kommuner, SOU 2002:46, (Site for final disposal of nuclear waste – feasibility studies in eight municipalities), Kommunerna – en av huvudaktörerna i kärnavfallsfrågan (KASAM:s rapport Kunskapsläget på kärnavfallsområdet 2004, SOU 2004:67 s. 79–135). Municipalities – one of the main actors in the nuclear waste issue (KASAM's report State-of-the-art in the field of nuclear waste 2004), Kärnavfall – demokrati och vetenskap (Rapport från ett KASAM seminarium 2003, SOU 2004:99), Nuclear waste – democracy and science (Report from a KASAM seminar 2003). The events and the general debate have also been covered extensively by Sundquist (2002) and Anshelm (2006).

- In 2000 SKB identified three places as suitable for continued studies and asked the municipalities for permission to carry out so-called site investigations.
- in 2002 SKB received permission from two of the municipalities. The sites being investigated are near the Forsmark nuclear power station in the municipality of Östhammar and in Laxemar near the nuclear power station in Oskarshamn. In both municipalities the municipal councils were almost unanimously in favour of the proposed site investigations.

During 1992–2006 SKB presented a total of seven RD&D programmes: 1992, 1994 (requested supplement of the 1992 programme), 1995, 1998, 2000 (requested supplement of the 1998 programme) 2001 and 2004. In each of the programmes most of the problems which occurred were solved but the focus of the programmes changed.

The programme which SKB presented in 1992 was an initial concretization of how it intended to proceed with the choice of a site where a repository could be built. Furthermore, for the first time it presented its plans to build an encapsulation plant immediately adjacent to CLAB in Oskarshamn. SKB argued for continued development of the KBS-3 method and at the same time reported on the investigations which had been made on alternative final disposal methods such as deep boreholes, long tunnels from land under the bottom of the Baltic Sea and medium-length tunnels. The Company also introduced the idea which had originally been put forward by SKN in its review of RD&D programme 89, and which implied that a final repository should be built step-by-step and, in the first stage, be used to demonstrate disposal of some 400 canisters. Only after such a step had been taken and reviewed should a decision on continuation of the work be taken.

Review of the RD&D programme 92 prompted the Government to request a supplement to the programme. The supplement was released in 1994 and contained *inter alia* a report on the criteria and methods which should be used in the work for site selection.

In the RD&D programme 95 the emphasis was on how SKB intended to carry out the plans for encapsulation and for location of a final repository which were reported in the 1992 programme. Important background reports were, *inter alia*, the report on the ongoing two feasibility studies, an overview of bedrock in the whole country and a model for the forthcoming safety analysis.[40]

The RD&D programme 98 was aimed at giving a general view of SKB's work and plans. It contained more detailed arguments than before for continued concentration on the KBS-3 method, as well as the reports of five completed and ongoing feasibility studies on the question of a site for a final repository and for the work on techniques and safety analysis. The programme also contained an initial proposal in the table of contents for an upcoming description of environmental consequences.

The Government's review led to a request for supplements. These were presented by SKB at the end of 2000 under the heading "Collected reports on method, choice of site and programme for site investigation". The report on method contained an analysis of alternative strategies and systems for the management of spent nuclear fuel. A comprehensive view of the feasibility studies which SKB had carried out in a total of eight municipalities was presented, as well as their conclusions,. The most important conclusion was that the Company had identified three different areas where it wanted to carry out site investigations. These areas were situated in the municipalities of Oskarshamn, Tierp and Östhammar.

When SKB presented the RD&D programme 2001 a review of the 2000 supplement of the 1998 programme was still ongoing. At the same time discussions continued between SKB and the three municipalities concerning implementation of the proposed site investigations. The RD&D programme 2001 focused on the questions of research and technical development. The following headings from the programme indicate the different questions which were dealt with: safety analyses, research on long-term safety, fuel, canister, buffer, backfill, geosphere, biosphere, climate change, natural analogies, Äspö laboratory, instruments and methods for site investigation, deep disposal,[41] encapsulation, alternative methods (this dealt with separation and transmutation as well as disposal in deep boreholes), demolition, other long-lived waste.

The RD&D programme 2004 was primarily aimed at illustrating the development of the production and sealing of canisters for final disposal of spent nuclear waste. This was motivated by the fact that SKB considered, within the coming three year period, submitting

[40] See Kasam report 2007:2 on safety analysis.
[41] At this time SKB often used the term"deep disposal" instead of the term "final disposal".

an application for a permit to build an encapsulation plant.[42] The programme contained, over and above, a main section on safety analysis and research with *inter alia* sub-chapters on fuel, canisters as a barrier, buffer, backfill, geosphere, biosphere, climate, social research and alternative methods. As in the RD&D programme 2001 "separation and transmutation" and "disposal in deep boreholes" were dealt with under alternative methods. The programme also contained a short main section on low- and intermediate-level waste. The section on social research was new. This was due to the fact that several consultation bodies, in connection with the review of the RD&D programme 2001, had stated their wish that the programme's technical and natural science part be complemented by a section on social science which included research on e.g. attitudes, decision-making in complicated community questions and social development in the long-term.[43]

SKB announced that the RD&D programme 2007 would give a central place to the deep disposal technique and continued work with alternative disposal methods. The intention is to report on SKB's system on how to manage the low- and intermediate-level waste in the RD&D programme 2010.

Some changes in the structure of State authorities took place during the 1990s. SKN was discontinued in 1992 and a large part of its work was taken over by SKI. Under the then Ministry of Environment and Energy, KASAM became an independent scientific committee called the National Council for Nuclear Waste. Its task - which is still valid – is to advise the Government on questions connected to nuclear waste management. This task also includes the independent review of SKB's RD&D programme every third year (over and above the review which is incumbent on SKI) and every third year to highlight the state-of-the-art on the topic of waste as well as providing a forum for dialogue on the nuclear waste issue. In 1996 a special authority was set up, the Board of the Swedish Nuclear Waste Fund (Kärnavfallsfondens styrelse), with responsibility for the administration of the funds which have been accumulated within the framework of the financial system.

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[42] This happened in November 2006, see below.

[43] The need to concentrate on social science research on the nuclear waste issue had been given prominence in, *inter alia*, KASAM's remarks on the RD&D programme 2001 (**SOU 2002:63 pp.115-124**). After this SKB developed a "social science research programme". Summary reports from different research projects have been released by SKB in the publications Social Science Research 2005 (Samhällsforskning 2005) and Social Science Research 2006 (Samhällsforskning 2006). There will be a further report towards the end of 2007.

2.3 2006–2060: Perhaps a switch of energy system – but nuclear power management must continue

The report on the physical science basis for climate change which the United Nations International Panel on Climate Change (IPCC) submitted in February 2007 painted a clear picture of the threat to climate development in the future. If we do not change the use of global resources, primarily reduce the emission of carbon dioxides, large parts of the world's populations will be forced to leave their present dwellings due to rising water levels and temperature increases which will make parts of the land area, mainly around the Equator, uninhabitable.

The decision in 1980 to phase-out nuclear power in Sweden was related to the fact that a suitable alternative would be available – suitable from the perspective that industrial production, employment and welfare development would not be threatened in the short- and medium-term. Just a quarter of a century later our energy production is integrated in an international industrial structure where the national arena has lost much of the possibility of deciding its domestic development. An important question here is which available energy systems can meet the needs of a growing global population with increasing real incomes. What shall a switch from a fossil fuel economy to another energy system be like? Can we today see some alternative which is commercially viable? What risks does this carry in such a case?

Paradoxically enough, the development of environmental policy towards far-reaching international agreements as a means of handling, for example, the increasing emissions of greenhouse gases, may lead to a potential conflict between national political goals – such as the phasing-out of nuclear power or non-exploitation of rivers – and the international goal to maintain the combustion of fossil fuels at an agreed level. How such a conflict – if it materialises – will be handled still depends to a large extent on which technical system solutions we choose and which political and economic choices we make. In Sweden for example, different economic and political incentives have led to the expansion of district heating systems based on biofuel. Moreover, electricity certificates have led to the introduction of renewable electricity generation. Despite the fact that conscious efforts are made to reach different environmental goals we can never ignore the fact that these choices are made in a society where resources are not limitless. Our choices today affect development both in the short- and long-term. There is, for example, a conflict of interest on a global level between, on the one hand, the United Nations decision to invest large resources to increase welfare for large parts of the world's present populations and, on the other hand, to use the resources to develop energy and power techniques which may affect climate and welfare only 30 to 40 years from now. Apart from this difficult overarching prioritising, energy-use and management of the existing energy system will, in the foreseeable future, become everyday concrete questions which must be handled and solved on a national level.

In November 2006 SKB submitted an application for a permit according to the Nuclear Activities Act to build an encapsulation plant for spent nuclear fuel immediately adjacent to CLAB in Oskarshamn. The application was submitted to SKI but it is the Government which will finally decide if the application shall be approved or not. Accordingly the use of nuclear waste has entered a more formal decision process and a new phase of events has been initiated.

The encapsulation plant is a step in the system for the final disposal of spent nuclear fuel – i.e. KBS-3 – which SKB plans. A final repository is also included in the system. To build both an encapsulation plant and a final repository for spent nuclear fuel a permit is needed according to two Acts, the Nuclear Activities Act and the Environmental Code. The Company plans to submit further applications required by these Acts at the end of 2009. In practice it will be firstly one application according to the Nuclear Activities Act for the construction of a final repository for spent nuclear fuel in either Oskarhamn or Östhammar, and applications under the Environmental Code for the encapsulation plant and the final repository. Applications under the Nuclear Activities Act are submitted to SKI and applications under the Environmental Code are submitted to the Environmental Court.

With the presently submitted application, a decision process has been initiated which will take a few years. Some fixed points for the continued work are the following:

SKB has, for its part, judged that a Government decision on the application for the different permits for the final disposal system will be taken around 2011 at the earliest.

On the condition that there is a positive decision in favour of SKB the construction of the plants will commence quickly. These could be put into operation in 2018.

After an introductory test-run related to the disposal of small quantities of encapsulated nuclear fuel, full-scale operation would commence at the beginning of the 2020s. At the rate of around 200 disposed canisters per year all fuel from the present Swedish nuclear power programme could be deposited in the 2050s.

At this point in time it is assumed that a specific decision will be taken on whether the repository shall be finally sealed or if it shall be left accessible in some form for a further period of time. Sealing of the facility would thus take place around 2060 at the earliest.

By way of conclusion it should be pointed out that the planning of a final repository for spent nuclear fuel in Sweden has, up until now, been on the assumption that there is an end point for the Swedish nuclear power programme. From 1980 and up to the presentation of guidelines for energy policy which Parliament decided on in 1997 (based on an energy policy agreement between the Social Democrats, the Centre and Left Parties) 2010 was such an end point. The energy policy guidelines which were decided in 1997 implied that a year for the phase-out of nuclear power should no longer be stipulated while at the same time a phasing-out of nuclear power was initiated (through the later decision on the closing of both reactors at Barsebäck nuclear power station).

Subsequently, SKB has, *inter alia*, in conjunction with its annual assessments of the future costs for final disposal of spent nuclear waste and for dismantling of the reactors – ultimately assumed that the remaining reactors have a lifespan of 40 years. This means that the volume of spent nuclear fuel will be somewhat larger than was considered when the planning horizon was 2010. Moreover, there is also clear support for these plans in the newly decided Act (2006:647) on financial measures for management of the rest products from nuclear technical work. In the present situation SKB assumes that approximately 9,000 tonnes of used nuclear fuel from the Swedish nuclear power programme will need final disposal.

However, it cannot be dismissed – for reasons indicated at the beginning of section 2.3 – that the view on the continued use of nuclear power in Sweden will change in the future. In this case, of course, planning of measures for final disposal of spent nuclear fuel must, like the measures for final disposal of other nuclear waste (including demolition waste) be made from revised starting points.

2.4 References

The report is based on a survey of committee reports, parliamentary publications and statutes during the period in question. A survey has also been made of the eight programmes for research, development and demonstration of methods for handling and final disposal of nuclear waste presented by the Swedish Nuclear Fuel and Waste Management Co (SKB) during the period 1986-2004, the review statements on these programmes published by KASAM and the Government decisions that have been made in response to these RD&D programmes. Another background document is SKB's application in November 2006 for a permit under the Nuclear Activities Act for an "encapsulation plant and a central interim storage facility for spent nuclear fuel at Simpevarp in Oskarshamn Municipality". Important sources on this are given in the text or in the footnotes. Other references are listed below.

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3 Construction and operation of the final repository

Erling Nordlund

3.1 Introduction

It will take 5 to 10 years to build the first stage of a final repository for spent nuclear fuel (construction time). The repository will then be operational for at least 50 years. During this operational period spent nuclear fuel will be deposited in completed parts of the repository while a successive enlargement of the repository will take place.

In this section an overview is given of the most important geotechnical and production issues which have to be addressed during this period.

Experience is drawn from the work involved in establishing mines which, to a large extent, resembles the construction of a final repository for spent nuclear fuel. The construction and operational time needed to establish a new underground mine is of the same order of magnitude as for a final repository. The difficulties and surprises encountered when establishing a mine should be used as a knowledge bank to meet the challenge which the construction of a final repository poses.

In this chapter some of the knowledge and experience from different stages of the construction and the following operation phase have been compiled and are discussed.

3.2 Requirements and conditions

According to SKB's RD&D programme 2004 **(p.113)** the choice of the rock construction technique shall be made based on the following:

- The construction and operation shall have limited effect on the safety functions of the rock and the other barriers

- Technical properties regarding bearing capacity and stability, fire safety, health and environment and accident risk shall ensure safety for the user and the visitor
- Investigations of the rock, work on the rock and operation may be carried out in parallel, but within separate areas.
- Further construction shall take place within the desired time and in a cost-effective way with certain flexibility
- Environmental impact shall be limited
- Residents living close by shall be disturbed as little as possible

The building of the deep repository can be divided into the following stages:

- Detailed investigation of chosen site
- Location
- Design
- Construction
- Operation

3.3 Detailed investigation of chosen site (time perspective 5–10 years)

A so-called site selection investigation is one of the activities used as a basis for the choice of the exact location of the final repository in the rock. During this investigation important factors concerning the stability of the rock construction are identified. When the place has been chosen more detailed preliminary investigations are carried out to finally decide on the location and design of the repository and to collect data for analysis. The design of the underground construction is based on data from the part of the rock mass where the facility will be built.

It may be interesting to study the experience gained from the establishment of mines so as to learn of the difficulties and surprises which may arise. The establishment of a mine depends on the position of the ore, above all in the vertical dimension, i.e. if the ore is a shallow or a deep-seated deposit. Even if a large number of mines have been established over the last 50 years, in principle there is no documented information on the establishment of them. The two most recently established mines in Sweden with underground mining are the mines of Boliden in Petiknäs and Lundin Mining in Storliden. The principal difference between these two mines is that the ore body in Petiknäs was larger and more deep-seated than in Storliden. This means that the geometry and position of the ore body in Storliden had been accurately determined before the construction and drifting of the incline/ramp (inclined tunnels from the ground surface to the repository) was started. In Petiknäs only a rough estimate of the geometry and position of the ore body could be made before construction of the mine's infrastructure began. To define the position of the ore body, prospecting holes were drilled with such precision from drifts in the mine that the mining layout could be decided. This should be kept in mind when planning the location and design of the final repository. The location of the ramp and investigation drifts should be decided so that exploration drillings can be carried out to provide a basis for the planned facility.

Detailed investigations carried out during the construction period are of vital importance in predicting areas with special geological conditions such as, for example, fracture zones, zones with metamorphosed rock (e.g. clay, chlorite, talc) and conductive zones. Since such zones are critical for the stability of and water leakage into the repository, it is important to know in advance which rock conditions the ramp and other underground structures will be driven through so that the rock mass can be sealed, stabilised and properly supported.

3.4 Design of repository (time perspective ≈5 years)

A redistribution of stress occurs when the rock is removed to create the underground construction. The stress levels increase in certain parts of the rock mass while they decrease in other parts. The redistribution of stress does not happen immediately but is a function of the length of the round (i.e., the length of the drill holes which are charged with explosives and subsequently detonated). The increasing stress can lead to failure and stability problems because of high compressive stress levels. Low stress levels can also mean an increased risk for stability problems, in that case in the form of blocks and wedges which are formed by natural geological structures (discontinuities). The design of the repository comprises calculation of the secondary stresses (after removal of the rock) and deformation, identification of the areas within which the strength is exceeded and potential fall-outs and design of rock support (e.g. bolting and shotcrete lining).

The primary state of stress in Sweden is characterised by high horizontal stresses. If the underground constructions are placed at a distance equivalent to more than three diameters (if the tunnel is circular) or span widths (if the tunnel has another form) from each other, the tunnels will not affect each other. In this case, the greatest secondary stress will occur in the roof and the floor (greatest compressive stress). The stress magnitude will be greater than the maximum virgin stress magnitude at the same depth. The secondary stress in the walls will be decreased compared to the virgin state of stress. At the depth at which a final repository will be built (500 meters) a damaged zone may be formed around the tunnels consisting of drift-related damage (blast damage) as well as damage which was caused by the secondary stress exceeding the strength of the rock. The largest damage zone may therefore be formed in the roof. A similar damage zone will be formed in the floor of the tunnel. The combination of damaged rock and the decrease in stress which occurs in the walls as a result of the excavation increases the risk for gravitational rock failure in the walls. It is therefore important to have an understanding of how the damaged and disturbed zones behave mechanically and hydrogeologically. Damaged rock contains more fractures which means that the stiffness and strength are reduced. The studies which have been carried out up until now have focused on how to define different types of zones but no one has been able to decide and describe how the stiffness and strength vary in the damaged zones. There are a number of scenarios:

(i) The stiffness decreases more than the strength. This means that the stress (the load) decreases more than the strength compared to the undamaged conditions and the construction is thus more stable than if the bedrock is undamaged.

(ii) If the strength decreases more than the stiffness, the stress will decrease less than the strength compared to an undamaged case. The risk for instability has thus increased.

(iii) If the stiffness and the strength decrease by the same amount, the walls and roof will be relieved compared to a case without damage.

Research has shown that the hydraulic conductivity in the blast-damaged zone increases compared to its natural state and that the risk for leakage increases due to a large number of new fractures being formed and the natural fractures being opened as a result of the blasting. In the damaged rock therefore, there should be more possible flow paths for groundwater. There are, however, studies which have shown that the hydraulic properties change so that leakage decreases instead. An increased knowledge of the rock properties and behaviour in the damaged/disturbed zone is important to make the design of the final repository as good as possible.

During excavation the rock is secured with a temporary support which is later supplemented so that permanent support is obtained. Moreover, water leakage during the excavation and in the operational phase is a problem which must be addressed. Possible water leakage is prevented through sealing of the rock mass. This is done through cement slurry (or some other grouting agent) being pumped into the rock mass via boreholes (grouting).

An extensive pre-investigation programme is needed to propose temporary support and a plan for the grouting activities. No matter how good this programme is, unforeseen behaviour in the rock mass may occur. A plan to solve different difficulties should be available at the start of construction. The underground construction should be designed with the help of engineering and numerical methods.

A new European norm for the design of rock constructions shall be fully introduced in Sweden within a few years. A large research programme involving the study of probabilistic design, especially with regard to the new European norm, is being carried out within SveBeFo's[1] framework programme. SKB is one of the main financers. The knowledge and methods resulting from the programme should be applied in the design of the final repository. SKB has also, via *inter alia* SveBeFo, initiated research projects, aimed at increasing the understanding of the grouting mechanisms, which material properties are required (particle size) and how grouting shall take place in a practical way. Since Sweden is one of the

[1] Stiftelsen Svensk Bergteknisk Forskning.

countries at the forefront of research within the field of grouting, the knowledge necessary to deal with any water problems which may occur in connection with construction is deemed to be available. There are, however, still difficult problems to overcome. One such difficulty may be when a high conductivity zone with extreme pressure and flows is encountered during excavation. An example is the Hallandsås tunnel.

3.5 Building of the repository (time perspective 5-10 years)

The excavation of tunnels, ramps and the other underground constructions can be done with the help of conventional methods, e.g. drilling and blasting, or with mechanical excavation (full-face drilling methods, TBM). Both methods damage the remaining rock but the extent of the damage is considerably less with mechanical excavation. The effect of the excavation method has been studied in, among others, the Äspö laboratory. Competence is available in Sweden to carry out both methods. A number of successful full-face drilling projects have been realized in Sweden, e.g. Klippens power station in the Ume river. The conventional method of drilling and blasting works in most types of rock masses found in Sweden.

The disadvantages of using the full-face drilling method are that it is generally much more expensive than conventional drilling. Moreover, it is limited with respect to geometry (curves in the tunnel direction) and cross section. The advantages are that excavation can be continuous, without interruption, e.g. for ventilation of explosive gases, and a smooth and speedy progression is obtained. Moreover the method may require fewer rock support measures.

At the request of SveBeFo research is being carried out into the causes of the delays and increased cost of the tunnel projects, but this is in an early stage and has not yet produced any results. It can generally be said, however, that the bottlenecks in the tunnel excavation are often related to the unexpected need for rock support measures, which is why it is important to re-emphasise that an adequate pre-investigation of the the rock mass has to be carried out.

In the establishment of a mine, ramps are used only if the excavation depth is shallow. The cost of sinking a shaft is so high that it is not economically justifiable. If, on the other hand, the mine is several hundred metres deep, the system for hoisting (ramps and/or shafts) is decided by tradition. Since a large volume of rock shall be hoisted during the construction of the final repository, probably the most advantageous solution technically and economically is to start with excavation of the ramp. The shaft can then be excavated with full-face drilling. This method means that a pilot hole (a hole which can be some decimetres in diameter) is drilled. Thereafter a large drill bit is mounted on the end of the pilot drill rod. Raise boring takes place when the pilot drill rod draws the reaming drill bit through the rock, whereby a hole with a much larger diameter is created. In principle, when the shaft is finished, all hoisting takes place via the shaft since this is the cheapest alternative. The shaft can later be used to transport backfilling material to the canister hole and repository tunnels.

3.6 Operation of the repository (time perspective 50–60 years)

Not all underground constructions in a mine are designed to have the same lifespan. The drifts which are nearest the excavation, e.g. stopes in a cut and fill mine or cross-cuts in a sub-level caving mine, have a lifespan of months to a few years while, in principle, inclines (ramps) and hoisting shafts have the same lifespan as the mine. When road and train traffic tunnels are built, a lifespan of around 120 years is aimed at. Consequently, experience from the underground constructions for infrastructure (road and rail road tunnels) should be studied.

An underground construction is already affected/damaged during the construction phase (e.g. by blasting). It will thereafter, during its entire lifespan, be influenced by processes which can affect stability. The local structural geology together with the orientation of the construction are important factors for stability. It is not only rock which is included in a rock construction; the tunnels are also often supported with rock bolts and shotcrete which decompose. The bolts rust while the shotcrete leaches. If the shotcrete is reinforced with steel fibre or steel mesh, this can also rust. Heavily rusted bolts lose their load-bearing capacity and rock bolt support must be supplemented with new bolts. Leaching of the shotcrete means that the concrete is weakened. This shotcrete should be removed before new material can be sprayed.

Underground constructions therefore need to be maintained to obtain a sufficient lifespan and ensure that secure conditions may be upheld. For the maintenance of an underground construction to be cost-effective its condition must be assessed, i.e. if it is necessary to take further measures or not. This assessment may result in a recommendation for possibly remedial measures, e.g. anchorage of potential instabilities with the help of rock support (bolting, meshing and shotcreting). Another recommendation may be that the rock be scaled so as to remove the loose rock and leached shotcrete. Thereafter, further measures are taken to minimise the effect of the decomposition processes or, at least to prevent the processes leading to rock failure and collapse which might jeopardise safety. Even if stability-enhancing measures prevent potential collapse and rock failure, they may, nevertheless, be taken too late from a cost-effective point of view. If measures are taken early enough, deterioration of the construction can be limited, the cost of measures decreased and further deterioration reduced.

Since there are no general methods available for assessing the condition of the underground construction with regard to its stability (before visual damage is observed), a number of stable constructions are probably repaired and reinforced while a number of unstable constructions are not discovered until they have collapsed. In certain cases also, relatively harmless initial damage can result in extensive damage and collapse in the long-run. General methods to assess the conditions which make early discovery of damage possible are therefore necessary so as to carry out cost-effective maintenance of the underground construction.

Fire can have catastrophic consequences

Over the last ten years there have been a series of tunnel fires around the world where people have perished. Examples in Europe are the Mont Blanc tunnel in 1999, where 39 people died, Kaprun in 2000 with 155 dead and the Gotthard tunnel in 2001 with 11 dead. A number of fires, without fatalities, have also taken place *inter alia* in the tunnel under the English Channel in 1996. The damage caused by these fires was partly very extensive and has lead to intensive debate and research into tunnel security in Europe.

The extent of the damage depends *inter alia* on the intensive heat release and aggressive combustion fumes.

A number of factors contribute to the fact that tunnel fires are often catastrophic. The spread of the fire is often very rapid. A lorry which catches fire may be engulfed in flames within a couple of minutes, which means that the spread of heat is rapid. Tunnel fires generate enormous heat release which can reach temperatures of over 1,000° C. This causes immense damage to concrete reinforcements in tunnels. Large- and small-scale tests have been carried out but their common feature is the study of the impact on concrete. All the fires mentioned above occurred in tunnels with concrete linings with a thickness of between 30 and 50 cm. Concrete lining is not used in Sweden to any large extent. Most tunnels have a layer of shotcrete with a maximum thickness of 20 cm. In such a tunnel it is probable that the rock behind the shotcrete would be influenced by the high temperatures which are generated during a fire. The probable fracturing mechanism implies that slices of rock spalls from the walls and roof as the increased temperature propagates into the rock mass. In addition, there is a risk that the rock which is exposed to high temperatures is affected so that the physical and mechanical properties change. If the rock contains quartz the propensity for spalling is larger and moreover the quartz undergoes a transformation at around 600° C. Tests have also shown that mica can combat spalling.

3.7 Summary

Design and building of the repository will require a well thought out preliminary investigation programme, methods to master high water-bearing zones and better knowledge of the mechanical and hydrogeological characteristics of the disturbed and damaged zones. For the areas in the rock mass which are characterised by low strength and where a stability problem in the form of fall-outs can be expected, the experiences and results from SveBeFo's research programme "Probabilistic design with special consideration to the new European norm" should be used. During the building and operational phases it is important to address the problems of rock failure, fall-outs and changed rock properties caused by a possible fire. There is a further need to assess the condition of the rock construction so that proper timely measures may be put in place.

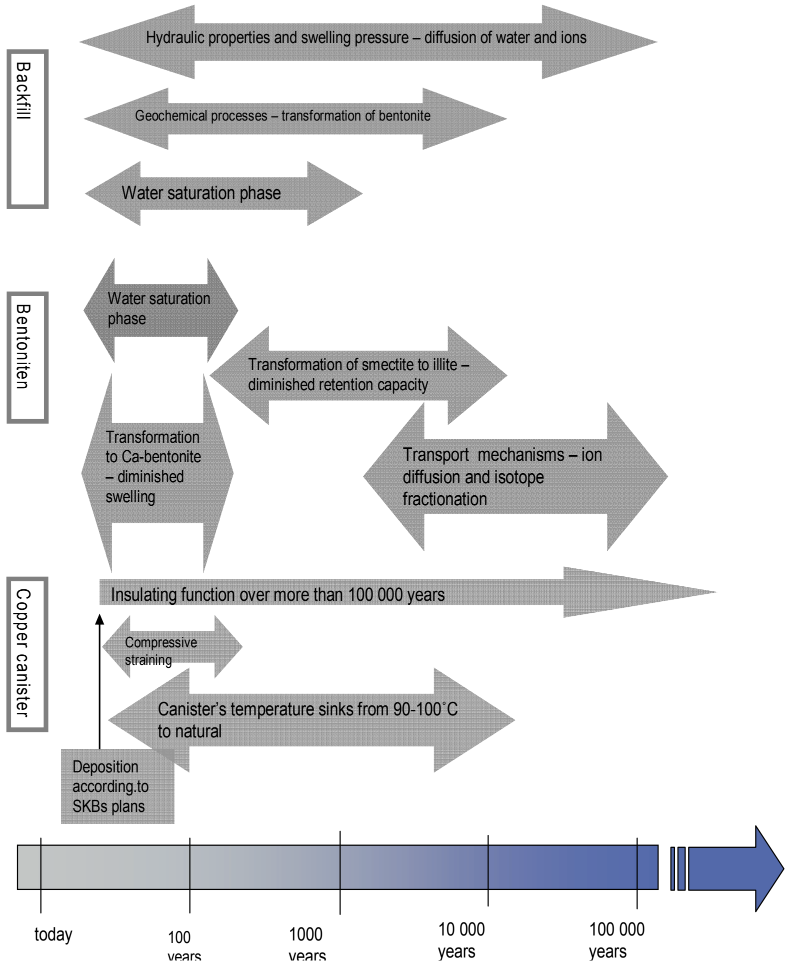
4 Engineered barriers

Willis Forsling and Hannu Hänninen

4.1 Introduction

Figure 4.1 illustrates different time perspectives which are of interest for the processes which are expected to take place in the final repository concerning the canister, the bentonite buffer and the backfill. As is clear from the figure, the processes have many different time frames but many of them greatly influence the long-term safety of the repository. As regards the backfill, SKB has not, as yet, disclosed which method it has decided to use, but the most important processes are not dependent on this.

Figure 4.1 Time dependent processes with regard to the canister, the bentonite buffer and the backfill



4.2 The canister from a time perspective

4.2.1 Requirements for the canister (time perspective >100,000 years)

The canister, which consists of different parts (Figure 4.2) is an important barrier in the repository as the canister prevents the groundwater from coming into contact with the radioactive spent fuel and isolates it from the environment. Both in Sweden and in Finland therefore, SKB and its Finnish counterpart (Posiva) have put in place special requirements for the copper canister (RD&D programme 2001/2004, TKS-2003/2006). The canister shall thus:

- Contain the fuel
- Be tight at deposition
- Be chemically durable during the lifetime of the repository
- Be mechanically durable during the lifetime of the repository
- Have little effect on other barriers
- Ensure that a critical state cannot occur

The outside of the canister has a copper shell and the insert is of nodular cast iron, i.e. exterior shell corrosion resistance combined with interior strength for long-term safe disposal. Both parts are therefore important in isolating the spent fuel from the groundwater over an extremely long period (>100,000 years), which is much longer than the operational time of any other industrially made product. To prevent the radioactivity leaking from the canister, fabrication techniques are required which result in a flawless canister with guaranteed material properties in the copper and cast iron which are optimised against all relevant damage mechanisms such as different forms of corrosion, creep, fracture, etc.

The methods for long-term safe disposal of spent nuclear fuel have been examined by SKB for more than 25 years. The preliminary technical documentation for the canister has been compiled within the framework of the so-called Dokap-project which deals with the construction, systems and processes developed for the fabrication and sealing of the copper canisters (SKB report R-06-1). The report also qualifies the fabrication and sealing of the canister for spent fuel. The documentation contains descriptions of the fabrication methods used in the production system, the quality and environmental management system for fabrication of the canister and canister factory, description of the welding technique used to seal the canister and the background concerning the choice of reference method for welding, descriptions of testing techniques for quality control of the sealing and bottom welding and the canister components. According to the qualification programme, the research and development work will continue with basic material studies, mechanical strength calculations and damage tolerance analyses. The components of the fabricated canister are the copper tube, the copper lid and the copper bottom, the insert of cast iron and the insert lid of steel (Figure 4.2).

Figure 4.2 Example of manufactured canister components: copper tube, cast iron insert and copper lid.

Source: SKB's RD&D Programme 2001 **(p. 273).**

The copper canister (50 mm wall thickness) protects the spent fuel from corrosion. It is planned that the copper canisters will consist of extruded seamless copper tubes (even microstructure and fine grain size, which are required for acceptable long-term properties and non-destructive testing) and forged copper lid and bottom. Two other alternatives for the fabrication of seamless tubes are forging and dorn pressing which also makes it possible to have an integrated bottom. Sealing and welding of the bottom are done with Friction Stir Welding (FSW) which is the chosen reference method (another possible technique is electron beam welding). The reliability of the FSW process has shown that the smallest intact copper thickness in the welding of the seal is expected to be 40 mm. Work to further improve the FSW technique is continuing. After the fuel has been placed in the canister the insert is sealed with a steel lid which is tightly screwed on. Thereafter the copper lid is welded onto the copper shell and the tightness is controlled with non-destructive testing.

The copper material must first and foremost meet the requirements according to the ASM UNS C10100 (Cu-OFE) or EN 133/63:1994 Cu-OF1 standards. Over and above these requirements it is required that oxygen < 5 ppm, phosphorus 30-70 ppm, hydrogen < 0.6 ppm and sulphur < 8 ppm. Furthermore, it is intended that the grain size shall be < 360 μm (examination by ultrasound possibly requires even smaller grain size). The inserts of the canisters are made in the shape of a cassette of square steel tubes for the fuel channels. Thereafter the inner container and bottom are made by casting the cassette into cast iron. The cast iron must meet the requirements according to the EN-GJS-400-15U standard.

Three methods of non-destructive testing are used to test the canister. Pore defects are discovered by x-ray radiography, ultrasound indicates defects not entailing volume, e.g. incomplete penetration, and with eddy current testing, defects near the surface are disclosed. Since the welded surface must withstand corrosion, it is important that there are no surface defects in a finished canister. Acceptance criteria will be determined for all parts of the canister including the welding. To qualify non-destructive testing methods it must be determined if the acceptance criteria comply with the test methods. To guarantee that the fabricated and sealed canister fulfils the requirements of the construction prerequisites a qualification programme for production, welding and non-destructive testing is needed.

4.2.2 Fabrication questions (time perspective 1–50 years)

Since the mechanical properties in cast iron are largely dependent on the dimensions of the cast body, testing of the material must be made for the finished inserts. Up until now these studies have shown a large distribution in ductility and fracture toughness which depend on both cast defects and on inhomogeneity of the microstructure. The mechanical properties have, up until now, not wholly met the stipulated requirements. The likelihood that a critically large defect will arise increases with the size of the components. The assumption that the largest defect controls the load-bearing capacity of the canister thus lowers the maximum allowed load in the larger components, so-called size effect. The casting process, like the specification of the cast iron, EN-GJS-400-15U (EN 1563), must be optimised on the basis of the above-mentioned limitations. Reliable material data for the cast iron insert is needed as input data to calculate the mechanical strength, e.g. when the effects of climate and geological changes are analysed.

After all the production phases – forming, machining and welding – plasticizing and residual stresses will appear in the material. The plasticizing and residual stresses must be measured and modelled because both can have a large influence on creep and stress corrosion when the canister has been placed in the final repository. The highest permitted value for residual stress, which should be less than half of the yield stress, must be decided. Furthermore, the need for different techniques to control residual stress, e.g. through stress relief anneal or mechanical surface treatment methods must be evaluated. Plasticizing occurs especially in and around the welded area and can negatively influence the local creep ductility and corrosion properties.

The aim of non-destructive testing (NDT) is to make sure that the components do not have deviations and discontinuities in the material structure, which may influence the long-term function of the canister during handling and in the final repository. Defects will exist in the copper canister after fabrication, but only a few (0.1%) canisters are allowed to have larger faults than are permitted in the acceptance criteria for the non-destructive testing (RD&D programme 2001). Acceptance criteria have not yet been specified. It is assumed that these unacceptable defects may cause water leakage in the canister within a 100,000 year period.

Bowyer (2000) has made a compilation of all conceivable material and fabrication defects and residual stresses which may appear in the copper canister and cast iron insert. Above all it is important to chart the defects in the welded lid of the canister. From the corrosion point of view it is important to minimise the formation of these defects. The size and shape of different initial defects must be measured as carefully as possible. The requirements for maximum grain size are important here also so as to facilitate ultrasonic testing. The acceptance criteria for the initial defects must be based on the best available NDT methods. Sensitivity of the NDT methods must be verified with the help of metallographic and microscopic investigations of diverse defects and the POD-diagram (probability of detection) for defects of different sizes, shapes and location must be generated. Probability analysis of the canister strength would be useful in determining and evaluating its durability for the loads which will arise in the final repository and which consequently influence the long-term safety. Further qualification of the NDT methods which will be used in the final process of fabrication and sealing of the canister must be carried out for both the copper and cast iron components.

4.2.3 Durability of the canister (time period >100,000 years)

The prerequisites for construction consist of, on the one hand, the need for safe handling and lifting (up to 100 lifts without risk) of the canister at encapsulation and deposition and on the other hand the basic need for long-term safety in the final repository. The processes which are relevant for the long-term development and operation of the final repository, as well as climate and geological changes, must be identified. After deposition the canister will stand in humid air at a temperature of 90–100° C, which is the maximum temperature for the copper canister in the final repository, before water saturation of the surrounding bentonite occurs within a 10–15 year period (initial state). Salt deposition is not expected to occur on the surface of the canister. The thermal conductivity in metal is hundreds of times higher than in the bentonite and in the rock. Therefore the canister is expected to have an even temperature which will slowly decrease to the surrounding temperature within 10,000 years.

Corrosion properties

In the final repository the copper canister will be exposed to both general and local corrosion of different types in complex chemical, microbial and mechanical environments, which moreover vary in time and space. Three characteristic climate conditions are expected to occur during the lifetime of the final repository, which will influence the corrosion durability of the canisters in different ways. During so-called temperate conditions the composition of the groundwater is aerobic (oxygenated) for the first 200 years and thereafter the environment becomes oxygen-free. During permafrost conditions freeze-out and low water turnover can lead to an important increase in groundwater salinity. During a glacial state the melt water will reach to the depth of the repository but the redox buffering capacity of the rock implies that only oxygen-free water will reach the final repository. Under oxygen-free conditions the anaerobic (oxygen-free) corrosion is expected to be controlled by the supply of dissolved sulphide to the canister. According to the presently applied calculation model, corrosion attack is estimated to be less than 6 mm in the copper shell. The likelihood that the corrosion shall penetrate the canister is therefore low in a perspective of 100,000 years, even with regard to initial welding defects.

For stress corrosion to occur, special circumstances are required regarding tensile stress, aerobic environment with certain contaminants (ammonia, nitrite, etc.) and very low strain rate. During the first 100 or 200 years the copper shell is deformed under compressive stress. During the same period oxidising corrosion conditions will occur in the repository. The risk of stress corrosion during this phase must be evaluated very carefully. The threshold values for initiation and crack growth during stress corrosion in copper must be measured in the environment of the final repository under different types of loading. For other corrosion mechanisms such as general and local corrosion (pitting and crevice corrosion) a considerably better knowledge is available thanks to laboratory investigations and natural and archaeological copper funds. Progress has also been made in the modelling of these forms of corrosion. Calculation of the corrosion rate is, however, based on short-term experiments (from hours to several years). Therefore, it is unclear if these results are relevant enough to guarantee that critical corrosion mechanisms would not occur over very long periods of time. The corrosion properties of weld metals where the microstructures vary and are quite different from the base material have, up until now, been investigated only to a limited extent.

When the copper shell has been penetrated by some corrosion or fracture mechanism, groundwater will enter the damaged canister and seep into the gap between the canister shell and the cast iron insert. Since copper and cast iron are in contact with each other galvanic corrosion will occur in the cast iron. This leads to the development of hydrogen gas and increased pressure due to gas pressure and growth of magnetite inside the canister. Under anaerobic conditions corrosion of cast iron is nevertheless very low, less than 1 μm/year. Experiments should nevertheless be carried out to verify that galvanic corrosion in the actual configuration of the canister will not be likely in the repository environment. After some time the water will come into contact with the spent fuel and the tube material which is of zirconium. Therefore the fuel material itself will also be attacked by corrosion. In this event there are a number of active corrosion mechanisms and modelling of different processes must be based on many different assumptions. On the basis of the complexity and the possible interaction between different mechanisms, empirical studies under realistic conditions must be made in the future so as to better model how corrosion damage develops in the damaged canister.

Creep properties

The consecutive development of mechanical stresses of the copper canister can be divided into four phases: the water saturation phase, the temperate and permafrost phase, and the glacial and post-glacial phases. The water saturation phase begins soon after sealing of the repository. Isostatic build-up of pressure around the canister will occur owing to groundwater pressure and swelling of the bentonite. Pressure differences in the canister can arise as a consequence of uneven swelling of the bentonite or the density difference in it which causes bending stresses on the canister, up to 55 MPa. During the glacial phase the ice build-up causes a slow isostatic increase in pressure in the repository, up to 45 MPa. According to the strength calculations, the canister will withstand an external pressure of 110 MPa. Therefore the probability of a canister collapse is judged to be small but unexpected time-dependent effects may arise due to the creep of cast iron and copper within this very long time frame. A reliable collapse criterion must be demonstrated through laboratory tests and strength calculations. During the post-glacial phase a slow decrease in pressure will take place in the repository and earthquakes may occur which may influence the canister mechanically when existing fissures in deposition holes are activated and cause shearing.

After fabrication there will be a gap of 1.75 mm between the copper shell and the cast iron insert. This means that the copper must be able to be deformed by about 4–5% in the final repository. Slow deformation in a temperature area of 75–90° C which will occur in the repository under residual stress, together with pressure caused by the swelling of the bentonite buffer, will lead to creep of the copper shell all the way into the cast iron insert. The copper which is used must have a creep ductility (maximum strain before cracking) of at least 10% both in the base and the weld material even after long periods of time. Creep ductility should also be measured in the groundwater environment with extremely low strain rates. Also in connection with post-glacial earthquakes shear movements may cause plastic strain of the copper shell which should meet the requirements for plastic strain of 7% and creep strain of 7.7%. Over and above the base material, the creep ductility and creep life of the weld metal must also be satisfactory. A ductility of up to 11% is required in the cast iron insert which is a high value for the present material. The probability of canister break through shear movements in the rock at the deposition hole must be evaluated. Under these circumstances the temperature of the canister will be the same as the surrounding temperature. The importance of phosphorous alloying (50 ppm) for creep rupture resistance of pure copper must be explained mechanically. These mechanisms are needed for long-term extrapolation of available creep data. It is important to clarify creep properties in the weld metal, which may have different properties from the base material because of varying grain size and plasticizing. When creep data for all the parts of the canister are available, it is possible to make finite element calculations of the deformation in the entire canister.

4.2.4 Summary

The insert which is of nodular cast iron has not yet shown acceptable mechanical properties and therefore the casting process must be analysed and better controlled or some other type of material must be used. Casting defects must be analysed more carefully in the future and different NDT methods should be developed to detect defects.

In all circumstances a very profound understanding must be built up regarding the mechanisms which cause the welding defects in copper. For this an evaluation of different NDT methods is required to detect defects and certify the quality of the canisters. It is also very important that no macro-defects which can quickly break through the canister arise during fabrication.

More research must be aimed at the long-term properties of the copper canisters so as to better predict future scenarios. Corrosion research specially aimed at the mechanisms of stress corrosion and microbial corrosion of the copper canister needs to be carried out, in the first phase, under laboratory conditions, but in a longer perspective, also on site in the final repository, if possible. Additionally, mechanical properties including creep, plastic deformation and fracture toughness should be investigated and documented.

To guarantee reliability during the entire canister fabrication and final repository period, acceptance criteria must be developed for all the canister parts including weld metals. These criteria must take into account the material properties and defects, both surface defects and defects within the material in the copper shell and in the cast iron insert. Consequence analyses must be carried out to predict possible processes when the canister does not meet the stipulations required. It is also important that the acceptance criteria be verified with the NDT methods and that a quality system for canister fabrication is formulated.

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4.3 The bentonite buffer from a time perspective

4.3.1 The role of the bentonite buffer (time perspective >100,000 years)

The bentonite buffer which surrounds the canister has a key role in the safety of the repository and must meet a long list of requirements. The most important ones are the following:

- To keep the copper canister in place in the centre of the borehole to stop the canister from coming in direct contact with the surrounding rock and at the same time possess a certain degree of plasticity to be able to absorb small movements in the rock.
- To conduct the heat energy of the contained fuel away, i.e. the energy which is released with radioactive decay and which is converted to heat in the canister and its surroundings.
- To prevent the transport of radioactive substances and colloids.
- To prevent the groundwater, which often contains corrosive substances, from freely flowing to the copper canister.
- To maintain very low hydraulic conductivity and thus only allow transport of various dissolved substances through diffusion.
- Through absorption of the surrounding groundwater, create a swelling pressure which is sufficient to close the voids in the buffer and tighten the gap between the canister and the surrounding rock.
- To produce an unfriendly environment for bacteria.
- To allow the diffusion of gases (e.g. H_2) which have arisen during the possible corrosion of the iron insert in the canister, without creating permanent transport pathways and voids.

4.3.2 Properties of the bentonite (time perspective >100,000 years)

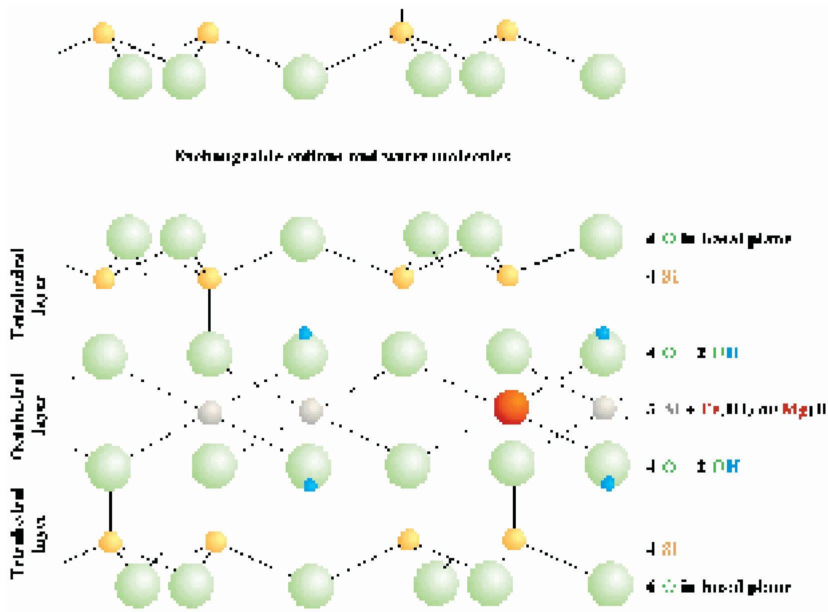
The role of the bentonite as a engineered barrier in the repository is based on its unique chemical and physical properties. It can swell to many times its original volume when placed in water and thereby form viscous (thixotropy) gels with water even in the case of quite small quantities of substances.

It has been demonstrated that the clay was formed through a natural transformation of volcanic ash several hundred million years ago which means that, under normal conditions, it can be expected to be chemically stable in the repository during the period in question (>100,000 years).

The mineral particles are very small (≤2 μm) and naturally agglomerated to larger units. To have the desired elasticity the bentonite must therefore be ground before it is pressed together into blocks which shall surround the copper canister in the repository. These blocks, e.g. in the form of large “pineapple rings”, must be sufficiently strong to be transported to the repository and placed around the copper canister without breaking. This process requires very large and efficient pressing tools and up until now SKB has not shown how this can be achieved in a satisfactory way.

For the buffer to have all the desired properties, the bentonite must consequently absorb the water between the silica layers so that the clay swells to several times its original volume (see Figure 4.3).

Figure 4.3 The structure of smectite (montmorillonite) which is the main constituent in bentonite.



The main constituent in bentonite is smectite (montmorillonite) which is a clay mineral with a structure as shown above. It contains silica in the form of tetrahedral layers (SiO_4) and aluminium oxide in the form of octahedral layers AlO_6).
Source: KASAM's State-of-the-art report 2001 (SOU 2001:35 **p. 197**).

In the first part of Figure 4.3 the lower part of the tetrahedral layers of adjacent mineral particles is shown. Water molecules and ions are found between the particles and ions with positive charge (cations) are bound to the particle surfaces which are negatively charged since the aluminium ions (Al^{3+}) in the octahedral layer have partly been exchanged for magnesium ions (Mg^{2+}).

The density of dry clay is around 1.6 kg/dm³ and the desired density for the bentonite buffer in the repository after water saturation is around 2.0 kg/dm³. It is the higher density which gives the buffer the properties which allow it to meet the requirements of the safety analysis.

4.3.3 Water saturation process and its importance (time perspective 10–200 years)

The process which leads to water saturation is called hydration (wetting of the mineral surfaces) and is very important for the safety of the repository. How long it will take is, of course, dependent on how quickly the groundwater comes into contact with the bentonite.

The process is described in detail in a previous report from KASAM (SOU 2001:35).

Water saturation (the hydration process) of the buffer will already begin during the construction period of the repository as the canister is put in place, which means that the bentonite will come into contact with water which is in equilibrium with the atmosphere at normal pressure. The water therefore contains both dissolved oxygen and carbon dioxide.

Depending on how dry the surrounding rock is, the hydration can take from some decades up to several hundred years. If the rock is very dry and the major part of the water is introduced during the backfilling there is, in KASAM's opinion, a risk that the water contains a series of undesirable contaminants from the ground mixture of crushed rock/bentonite or from the Friedland clay (see 4.3.2) depending on which backfill method SKB chooses. These contaminants can, in the long-run, negatively influence the buffer and impair its properties.

A very long hydration process also means that during the period when the radiation from the spent fuel in the canister is the greatest (i.e. the first 100 to 1,000 years) and the associated heat generation is proportionately high, the buffer may be partly unsaturated and will therefore not have attained all the desired properties.

Depending on how quickly and in what way the water is introduced for saturation and the swelling of the bentonite buffer the process will look very different which makes it more difficult to judge the function of the buffer in the short- and long-term.

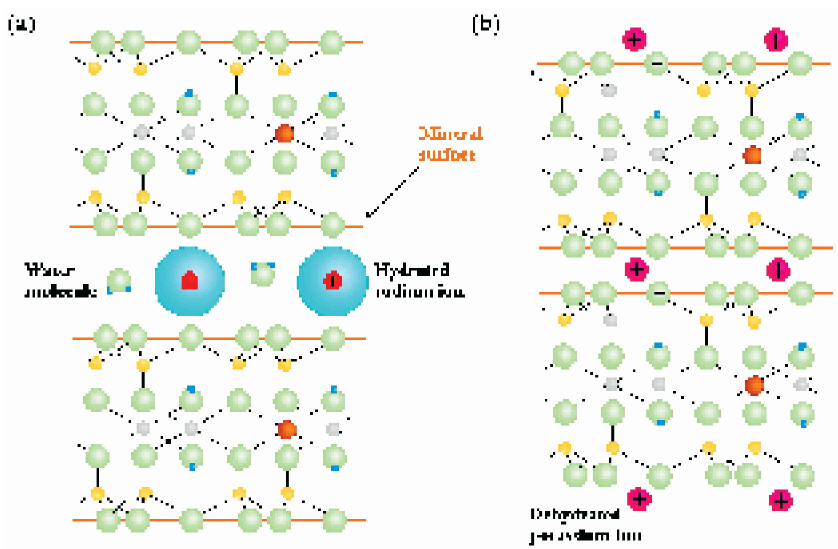
If the water, on the other hand, is introduced too quickly, e.g. through groundwater flow, there is a risk that colloidal particles (less than 0.1 μm) are pulled away from the buffer and may, in the worst case, be further transported on the particle surfaces together with the radioactive substances from a possibly damaged canister. However, a high flow velocity is probably only present during the first months or years.

4.3.4 Transformation to illite time perspective 100 to 100,000 years)

Another process which has been discussed in different contexts and has been put forward by many critics as an uncertainty in the long-term, is the transformation of smectite (montmorillonite) to illite in the bentonite buffer. Illite is a clay material which does not have such desirable properties as smectite. For example, illite has much less ability to absorb water and to swell.

Such a transformation means that many of the buffer properties are deteriorated so that they can no longer meet the requirements of the safety analyses (see Figure 4.4).

Figure 4.4 A comparison between the clay mineral: (a) smectite



Source: KASAM's State-of-the-art report 2001 (SOU 2001:35 s. 213).

In MX 80 (sodium bentonite from Wyoming, USA) (a) sodium ions are surrounded by water molecules and bound to the surfaces to neutralise the charge. The relatively large ion radius of these ions helps to maintain the distance between the layers in the smectite, which means that the water molecules have sufficient space. This is the reason why sodium bentonite has a large capacity for swelling and water absorption. The distance between the mineral particles grows when more water is absorbed. The formation of illite means that a part of the silicon is replaced by aluminium in the tetrahedral layer, which gives rise to a negative surface charge. (b) In contact with potassium-containing groundwater the surface charge will be neutralised by potassium ions (K^+). These ions easily emit those water molecules which are present around all the ions in the water solution. The potassium ions drained in this way are effectively incorporated into the voids between the tetrahedral layers of the adjacent particles. Illite forms tightly packed columns where the space is too small for the water molecules.

One key parameter in this context is thus the access to potassium ions in equilibrium with the buffer and another critical factor is the temperature. Calculations have shown that at a temperature of around 100° C and with a potassium content of 200 ppm, the transformation process can take 100 to 100,000 years depending on which kinetic model is used.

It is therefore probable that the process is already clearly noticeable after a few hundred years. When the water which is used for water saturation of the bentonite is supplied mainly via the backfill (if the rock is dry) there is a risk that leached potassium ions and other dissolved substances hasten the process. Since the backfill consists of fine grain material with a large surface area, solution, ion exchange and adsorption, will be central processes for the water transport (see the following section on the backfill).

4.3.5 Transformation to calcium-bentonite * (time perspective 10 to 200 years)

A less dramatic but considerably quicker process is ion exchange between sodium ions (Na^+) in the bentonite and calcium ions (Ca^{2+}) in the groundwater, which results in a transformation from Na- to Ca- bentonite and an appreciable deterioration in water absorption and with that, decreased density in the buffer.

The difference in hydraulic conductivity between Na- and Ca-montmorillonite is, however, significant at densities below 1.6-1.8 kg/dm^3. The retention ability of the barrier (ability to retard transport) deteriorates because the transport of certain ions can increase up to ten times.

During the construction period of the repository (around 40 to 50 years) many of the processes in the bentonite buffer (water saturation, ion exchange, etc.) are influenced by the relatively high oxygen and carbon dioxide concentration in water, which is in equilibrium with the surrounding atmosphere.

To this may be added possible contaminants from activities in connection with the construction of the repository, i.e. exhaust gases from engines, oil spills, etc.

4.3.6 The influence of pore water (time perspective 1 to 200 years)

The carbon dioxide pressure of air, pCO_2, influences the carbonate content (CO_3) in the water and can lead to formation of a complex with the metal ions and precipitation of carbonates with low solubility, e.g. $CaCO_3$ (calcium carbonate) in the buffer.

An increased quantity of dissolved oxygen in water ($O_2(aq)$) increases the oxidising ability (the pe-value) and in contact with the bentonite the sulphide-containing (S^{2-}) contaminants such as pyrite (FeS_2) will oxidise and lower the pH-value. The acid formed may then react with and be neutralised by the calcium carbonate in the buffer or the carbonate ions in the water.

It is important that the pH-value in the buffer's pore water is kept at a constant level since the adsorption ability of the particle surfaces is strongly pH-dependent. The conditional (local) adsorption constants (actually distribution constants, the K_d-values) for different radionuclides which are used in SKB's models are moreover valid within a very narrow pH and concentration range.

According to model calculations the pH-value shall reach a maximum value of 7.6 after 100 years caused by the dissolution of calcite ($CaCO_3$). After this, the model predicts a decrease in the pH-value in the whole buffer to a minimum of 6.35 after 1,000 years.

There is reason to take the pH-changes in the buffer in all seriousness since low (or too high) pH-values cause a series of undesirable consequences such as increased corrosion of the copper canister, increased solubility of silica and transformations in the buffer (e.g. formation of illite).

4.3.7 Transport mechanisms (time perspective 1,000 to 100,000 years)

One main function of the buffer is to stop, or in any case retard, transport of the radionuclides from a possibly damaged copper canister to the surroundings. There is a large number of published papers regarding the transport velocity of different isotopes through the buffer.

The transport mechanism for positively charged ions (cations) should be, in principle, different from that of negative ions (anions) since the particle surfaces in the buffer in general are negatively charged, which means that the anions are repelled while the cations are attracted. Moreover, there are different precipitation and ion exchange reactions, redox reactions, etc.

The diffusion coefficients for different radioactive substances are conditional, i.e. they depend on the density of the buffer, the pH-value, temperature, etc.

If the bentonite is completely water-saturated ($\rho = 2.13$ kg/dm^3) the conditional transport velocities are often in the magnitude of 10^{-11}–10^{-12} m^2/s, which enables a rough estimate to be made of the time required for a radioactive substance to diffuse through the buffer which is around 0.35 m thick (the distance between the copper canister and the surrounding rock) with the help of the equation $x^2 = 2Dt$ where x represents the distance, D is the diffusivity (specific transport velocity) and t is the time. If D is set at $2 \cdot 10^{-12}$ m/s and x = 0.35 m, t becomes ≈1 000 years, which may be considered to be relatively satisfactory. It must be remembered nevertheless that this value is valid only for maximum favourable conditions; with a lower swelling pressure the diffusion time through the buffer becomes considerably shorter.

4.3.8 Isotope fractioning (time perspective 1,000 to 100,000 years)

One consequence of the long diffusion time (≈1,000 years) is that the process will most likely give rise to isotope fractioning, i.e. a separation of the different isotopes of the diffusing elements. In general the lighter isotopes of an element are transported faster than the heavier ones whether they are radioactive or stable.

The differences in the transport velocity will generally be larger for light elements since a certain difference in mass becomes larger percentage-wise. But the velocity is also influenced by the transport mechanism, i.e. adsorption, ion exchange, complex formation, precipitation, etc. which contribute to longer diffusion times for heavier isotopes of the same element.

4.3.9 Summary

The role of the bentonite as a engineered barrier in the final repository of high-level spent nuclear fuel has been well examined in a large number of investigations and reports.

Most of the investigations deal with the properties of water-saturated sodium bentonite (MX 80) from Wyoming, USA. MX 80 has many good swelling properties in water. This means that the bentonite buffer can be very compact with low permeability of radioactive substances, even when these are in the form of ions and gases.

One disadvantage is, however, that sodium bentonite in contact with the groundwater can be transformed so that its properties partly deteriorate. This depends, for example, on the sodium ions in the bentonite being exchanged for calcium ions from the groundwater (through an ion exchange reaction). The result is formation of calcium bentonite which has inferior swelling properties. The bentonite barrier therefore becomes less tight. As described above, this reaction can occur relatively quickly, perhaps within 200 years. This process is more or less unavoidable when unsaturated bentonite comes into contact with the groundwater. However, this is not a question of any catastrophic change in the properties of the barrier, even if the time for the transport of radioactive substances through the buffer is shortened.

Another reaction which has a negative influence on the bentonite in its role as a engineered barrier is that the principal ingredient in bentonite (smectite) may be converted to illite. This can happen through the sodium ions in bentonite being exchanged for the potassium ions from the surrounding water. The potassium ions can, for example, come from leaching of rock and crushed rock (potassium feldspars) or cement which is used in the construction and the ions can be transported with flowing water or through diffusion. This transformation process takes much longer, up to 10,000 years or more – see the discussion above – but also implies a more thorough deterioration in the properties of the buffer with regard to swelling, elasticity and retention (retarding) of radioactive substances.

Since this reaction takes a very long time, the radioactivity of the fuel has, to a large extent, had time to decay. The process therefore cannot be judged to be a threat to long-term safety. However, contact of a long duration with the potassium-containing water should be avoided at an early stage.

The swelling of the bentonite – and thus the properties and function of the barrier – is also influenced by how fast and in which way the water comes into contact with the bentonite and by the contents of the water in the form of dissolved substances (e.g. its salinity).

Most of the positive properties of the buffer are linked to a water-saturated bentonite, but as is described above, the composition of the water is of great importance (e.g. the concentration of potassium and potassium ions). It is also of great importance how evenly distributed the water is in the buffer. An uneven distribution means that the buffer will have different properties in different directions. A totally dry bentonite for example has not the tightness, elasticity and other physical properties desired. It is thus important that the bentonite has as even a supply of water as possible during the first 100 years after the canister has been deposited and that the water does not contain any substances harmful to the buffer.

SKB has not demonstrated how to produce sufficiently mechanically stable blocks of bentonite (e.g. in the form of “pineapple rings”) which can be transported and placed around the copper canister. The bentonite blocks will certainly weigh hundreds of kilogrammes each and fabrication of the blocks requires very big and powerful press tools which hardly exist today.

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4.4 The backfill from a time perspective

4.4.1 Requirements for the backfill (time perspective >100,000 years)

The backfill of all the deposition tunnels and other cavities in the rock which were created in conjunction with the construction of the repository is a critical process for the continued operation of the repository.

The requirements for the backfill can be formulated in a number of sentences:

- The backfill shall have a stiffness which minimizes the upward expansion of the buffer so as to maintain the buffer's density.
- The backfill shall have a hydraulic conductivity which is comparable to that of the surrounding rock. The deposition tunnels and access roads can otherwise form pathways for water and gas transport in and out of the repository.
- The backfill shall have a swelling ability which guarantees a sufficient swelling pressure against roof and floor and which can

tighten the possible effects of channel formation and creep movements.

- The diffusion of radionuclides, radioactive gases, colloidal particles and other harmful substances shall be low.
- The backfill must not have any negative influence on the barriers in the repository which presents requirements on the chemical composition.

4.4.2 Different concepts for the backfill (time perspective 1 to 100 years)

According to RD&D programme 2004, SKB, together with its Finnish counterpart, Posiva, is studying a number of different concepts for backfill of tunnels. The concepts being analysed in SR-Can are either a 30/70 mixture of buffer material and crushed rock which is compacted directly in the repository or block-pressed Friedland clay (see below).

In a newly published report from SKB (R-06-71) the material in the backfill is divided into three different categories:

1. Bentonites which consist of different types, high-grade, low-grade Na- and Ca-bentonite clays from the USA, India and Europe. The high grade clays shall be used together with ballast (crushed rock).
2. Smectite-rich mixed clays from the Czech Republic and Germany (Friedland clay).
3. Mixtures of bentonite and ballast which contain 30, 40 or 50% bentonite and crushed rock with different particle size distribution alternatively sand.

Apart from the long-term safety aspects the total cost will certainly be an ultimate factor which SKB will take into consideration since large quantities of material will be needed.

One advantage of a 30/70 mixture (30% bentonite plus 70% crushed rock) is that part of the rock from the tunnel construction can be reused which has a positive environmental effect. This concept, however, presents requirements on the mineral composition of the ballast used. The exposed surface of crushed rock will, of course, be increased millions of times compared to the original rock, and this will have chemical and physical consequences. Potassium and silicon which leach from potassium feldspars can cause transformation to illite or cementing of the buffer, while other minerals such as e.g. carbonates and pyrite (FeS_2) may cause cementing or corrosion.

In this context, cementing means that a low soluble compound (precipitate) is formed at the expense of the dissolution of a more easily soluble compound.

To achieve as tight packing as possible between the bentonite and the crushed rock, an optimal particle size distribution is needed which means that the ballast (crushed rock particles) has been ground to a size in the order of <5 mm, which will demand much energy.

At present, two principally different methods are being investigated for application of the backfill in the tunnels. One method implies that the material is first compacted to blocks ($\approx$0.24 m^3) which, together with pellets, are used for backfilling the tunnel at a speed of around 6 m/per day.

The other method is to fill and compact the material on site in the tunnel.

One difficulty with this method is to achieve sufficiently high density in the backfill nearest the roof of the tunnel and it will also be susceptible to leaking water.

4.4.3 Importance and speed of water saturation process

At water saturation (hydration) the bentonite will swell and particles from the finely ground rock will then contribute to the stiffness aimed at resisting the expansion of the bentonite buffer when it swells. The properties of the mineral particles with respect to water absorption in conjunction with swelling – but also leaching, charging and adsorption ability – will be greatly significant for the functioning of the backfill. The interaction between ballast and bentonite on the molecular level is also critical. The aim is to produce a very tight connection between bentonite and ballast which *inter alia* means that the mineral particles will be hydrophilic (have high wetting ability) to minimise the containment of air which would cause a deterioration in the properties.

The properties of the backfill, as well as the bentonite buffer, depend to a high degree on the conditions during the water saturation phase. How the conditions of the rock influence the wetting phase of the backfill in the repository tunnels has been investigated for three different concepts and the result reported in SKB's report TR-06-14. In the calculation, variations have been made of the hydraulic conductivity of the rock matrix, the distance to the water supply limit and the presence of a permeable zone at the boundary of the rock surface.

The results show that the time until total water saturation varies from 0.5 years for the 30/70 backfill with 1 m between the fractures in the surrounding rock to more than 150 years for Friedland clay and 25 m between the fractures.

If the rock is completely dry (extreme case) the time until water saturation for the 30/70 mixture varies between 250 and 2,000 years and for Friedland clay between 250 and several thousand years.

It is the hydraulic conductivity in different types of backfill which controls the wetting velocity. The time difference to reach full water saturation in Friedland clay is about 10 times longer than that for the 30/70 backfill. The fracture frequency of the surrounding rock is most important, since the velocity of the water transport in the rock matrix is very low, $\approx 10^{-13}$ m/s.

If the permeability of the rock increases to 10^{-12} m/s water saturates both types of the backfill within a period of around 80 years. The total hydraulic interplay between the rock, buffer and backfill has been modelled in a 3D-model which simulates an infinite repository intersected with rock fissures. Depending on how much and in what way the water is supplied (through horizontal or vertical fissures) it will take between 10 and 600 years to saturate the whole buffer and 1 to 1,100 years to saturate the whole (99%) backfill.

The modelling also shows that the maximum temperature of the copper canisters (around 90°C) is reached after about 20 years.

The properties of the backfill are thus largely dependent on the degree of water saturation which may vary over 1,000 years. This means that the requirements put on the backfill are not met during the corresponding period of time, which should be taken into account in the calculation.

If wetting of different parts of the backfill occurs at different velocities (which is a likely scenario) this leads to a variation in the hydro-mechanical properties. The significance of this is not entirely clear.

The backfill nearest a fissure in the surrounding rock may be water-saturated rather quickly and swell while the material further away is proportionately dry and accordingly does not swell as much.

KASAM emphasised earlier - on examination of SKB's RD&D programme 2004 - how important it is that the backfill, in the first instance, maintains the tightness of the buffer when the bentonite around the canister is water-saturated, i.e. to establish resistance against the expansion forces which are created in connection with the swelling.

4.4.4 Hydraulic properties and swelling pressure of backfill (time perspective 1 to 100,000 years)

The capacity of the backfill to conduct water will also be largely dependent on the quality of the water supplied. These aspects have been investigated and described in a doctoral thesis (Clement, 2003).

The measured velocity for transport of water in the backfill varies between $4.5 \cdot 10^{-12}$ m/s and $3 \cdot 10^{-11}$ m/s where the higher value stands for a higher salinity in the inflowing water (16 g/l).

In SKB's report TR-06-71 some new criteria are reported to indicate an approved function of the backfill:

1. The swelling pressure in the backfill must not be below 0.2 MPa. A lower swelling pressure implies that the tightening against the walls and roof will not be sufficient to stop possible water flow.
2. The hydraulic conductivity must not exceed 10^{-10} m/s. A higher value causes the velocity of water transport through the backfill to be too high.
3. The backfill must be able to withstand the swelling of the bentonite buffer so that the density at the top of the copper canister is not below 1.95 kg/dm^3.

A hydraulic conductivity of 10^{-10} m/s is equivalent to the water moving a distance of around 3.2 mm/year. It can be expected that the diffusion of the ions and radionuclides are of around the same magnitude (or perhaps somewhat higher) and in the best case these processes cancel each other out but they can, in the worst case, interact. In such a case transport of the radioactive substances will occur through the backfill, through ion diffusion as well as through hydraulic diffusion.

The swelling pressure seems not to be as dependent on the salinity of the water as on how compacted the backfill is in dry conditions, i.e. higher specific weight leads to higher swelling pressure. At low compaction saline water seems to be advantageous in the formation of a high swelling pressure.

The backfill in these studies was the 30/70 type, i.e. 30% sodium bentonite and 70% crushed rock (granite) with a maximum particle size of 20 mm.

The relatively large granite particles in the crushed rock in relation to the bentonite particles make it risky to predict the properties of the backfill with regard to a number of parameters critical to the repository and it is very important to carry out full-scale experiments.

One conclusion reported in the above-mentioned doctoral thesis (Clement, 2003) is that pure bentonite blocks should be placed near the floor and roof in the backfill tunnels so as to ensure a sufficiently large swelling capacity in those areas where a free flow of water can be expected and prevented.

4.4.5 Geochemical processes (time perspective 1–10,000 years)

Chemical analyses of water which has been collected during the saturation phase in the backfill show that there are three principal reactions which control the geochemical properties, namely ion exchange between sodium and calcium in the bentonite, dissolution of gypsum ($CaSO_4$) and calcite ($CaCO_3$). This means that, to a large extent, a transformation from Na-bentonite to Ca-bentonite occurs along with water saturation in the backfill and the dissolution reactions together with the ion exchange give rise to changes in the hydraulic behaviour, e.g. the swelling properties of the backfill.

As previously mentioned in the section on the long-term function of the bentonite buffer, a transformation of the mineral montmorillonite in the bentonite to illite can be expected. This process is highly dependent on both temperature and the potassium concentration in the water. High temperature and potassium concentration lead to a quicker transformation. The temperature in the backfill is lower than in the buffer since it is further away from the copper canister, but on the other hand, it is expected that a higher potassium concentration in the water is expected depending on leakage from the crushed rock and other ballast material.

The bentonite in the backfill is also in very close contact with the ballast material which is why there is a risk of very quick transport of potassium ions and a relatively hasty process.

4.4.6 Mechanisms for ion transport (time perspective 10 to 100,000 years)

Even at the point of time when the backfill is water-saturated the mechanisms for transport of the ions and other substances will be partly different from conditions present in the bentonite buffer.

It can be expected that the principal transport mechanism of radioactivity and other dissolved substances through the backfill will be by diffusion. Hydraulic conductivity will be added to this, i.e. possible water transport through the material. Moreover, the mechanism consists of a series of other parameters such as ion exchange, reactions, complex formation, sorption and precipitation reactions, etc. The internal size relationships between the different parameters are influenced by the conditions in the backfill such as the density, particle size distribution, the number of reactive sites on existing minerals, the surface charge of different particles, the interaction between different types of particles in the backfill, etc.

The temperature gradient which may be present in the backfill, where the most superficial parts may have very low temperatures (under certain climate conditions below freezing point) while the backfill nearer the buffer will have a considerably higher temperature due to heat generation from the canister, also influences the process.

During periods with permafrost the water in the backfill will freeze far down into the repository which will lead to increased distance between the particles through the formation of ice.

Thus, when the temperature rises again entirely new flow paths can arise.

4.4.7 Summary

KASAM has emphasised in several statements on SKB's RD&D programme that the backfill is a very critical part of the whole KBS-3 concept. The goal is to create a tight mass which has the ability to conduct water comparable to the surrounding rock. Accordingly, the water must not find free flow paths down to the buffer and canister. The backfill shall also have a sufficient stiffness to be able to withstand expansion of the bentonite buffer which occurs when it becomes water-saturated. This is important to maintain the density of the buffer. KASAM has, in earlier statements, pointed out that the stiffness should be one of the properties prioritized in the backfill.

SKB is presently working on a series of different concepts for backfill of the deposition tunnels and access roads in the final repository for spent nuclear fuel. The alternatives which are of immediate interest for analysis in SR-Can are either a mixture of 30% bentonite and 70% crushed rock which is compacted on site in the repository or Friedland clay which is supplied in the form of compacted blocks. KASAM looks forward to SKB making its final choice of concept and an indication of the motivation for this choice.

The material in the backfill may be divided into a number of different categories, namely high and low-grade sodium and calcium bentonite clays from different countries, smectite-rich mixed clays (Friedland clay, smectite is a clay mineral) of different origins and mixtures of bentonite and crushed rock with different mixing relationships.

Which concept and which material will finally be chosen for the backfill naturally influences the conditions in the repository at different points of time and one must therefore, in this case, work with many different scenarios. Different mixtures of bentonite and crushed rock as well as pure Friedland clay will swell in contact with water. If the expansion can be limited the density will increase and the material will become tighter. How long this will take is obviously totally dependent on how much water is supplied and which type of material is used. In the above section on backfill we have tried to describe different water saturation scenarios from a time perspective.

That the material in the backfill is finely ground means that there is a risk that undesirable metals or other contaminants leach from the particle surfaces and come into contact with the bentonite buffer. The consequences of this are that the swelling properties and retention capacity for the radioactive substances may deteriorate.

There is also good reason for SKB to control and set limit values for certain types of contaminants in the material for the backfill.

4.4.8 References

Kärnavfall – barriärerna, biosfären och samhället.

KASAM:s yttrande över SKB:s Fud-programe 2004; (SOU 2005:47).

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Water saturation phase of the buffer and backfill in the KBS-3V concept (TR-06-14).

Hydraulic behaviour of bentonite-based mixtures in engineered barriers: The Backfill and Plug Test at the Äspö HRL by Mataena Clement, PhD thesis 2003.

5 Natural analogies

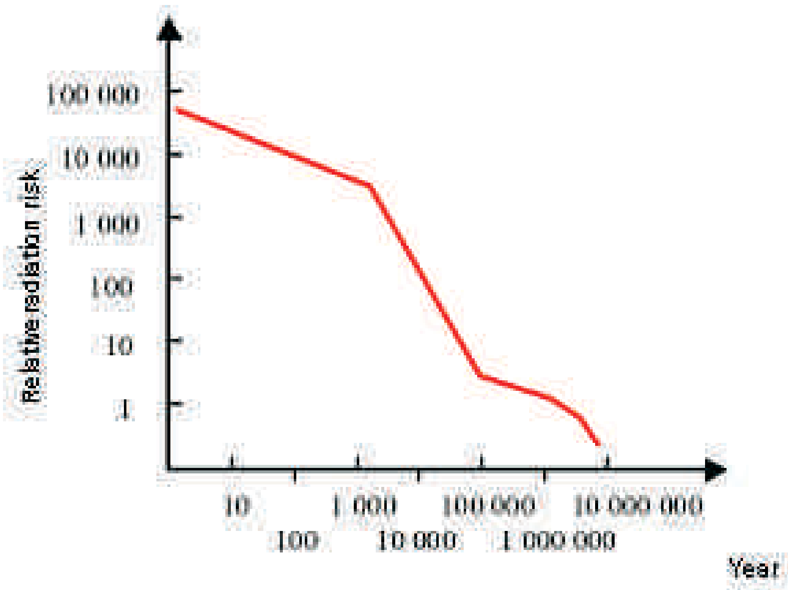
Sören Mattsson

5.1 Introduction, time perspective

A final repository for spent nuclear fuel and high-level reactor waste must be constructed so that the long-lived radioactive substances are retained in such a way that they cannot reach humans or any other living organisms. It is mainly through leakage into the groundwater, and to some extent via gaseous releases, that the activity could be transported from the repository. It is therefore important to have good models for these transport pathways. Such models must cover long periods (thousands to hundreds of thousands of years).

Figure 5.1 gives a rough picture of the danger of the waste in relation to the danger of the uranium, which is used in the nuclear fuel and Figure 5.2 shows the contents of a number of different radionuclides, all at different points in time after removal from the reactor. There is of course no tested transport model for these time periods. The models and data, which are used today, are a result of laboratory and field measurements carried out over the last few decades.

Figure 5.1 **The danger of spent nuclear fuel in relation to the uranium which nuclear fuel is made from (shown in years after removal from the reactor)**



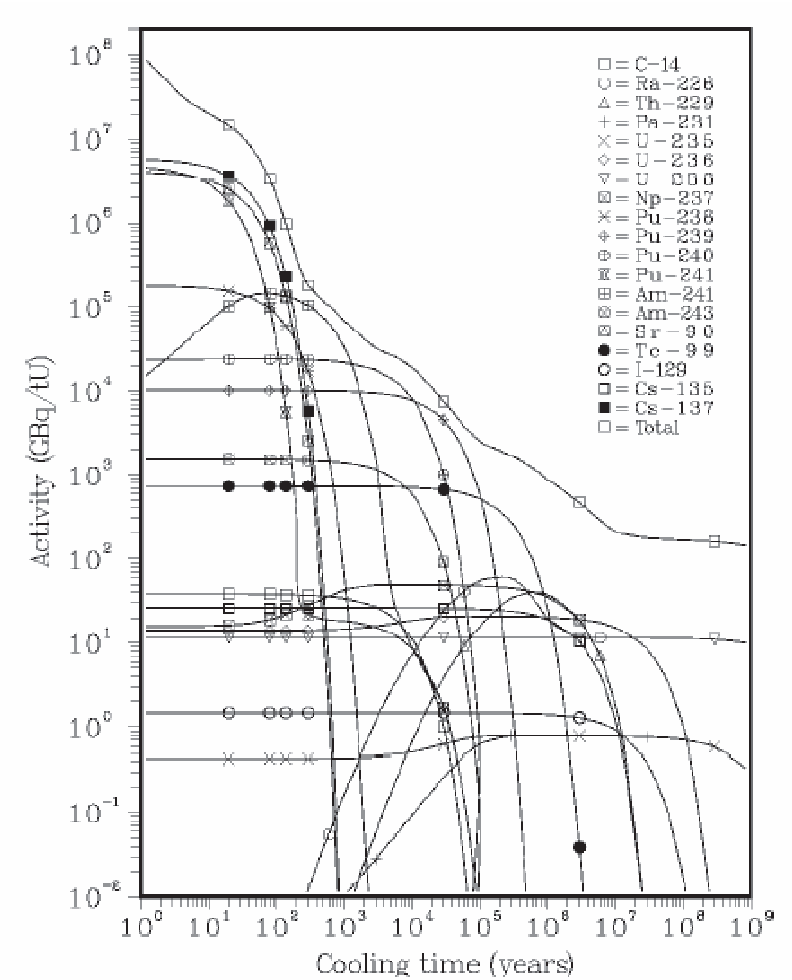
Source: L. Högberg, S. Norrby and B. Dverstorp, How to finally dispose nuclear waste for hundreds of thousands of years? SKI investigates the problems surrounding nuclear waste. Nucleus 16 (2), 1998, SKI, Stockholm.

One way of controlling the models and input data, which is used in safety analyses for a repository is to study so-called natural analogies. Natural analogies are understood to be the occurrence of material and processes, which resemble those expected in a repository. They make it possible to study repository-like systems, which have developed over geological time scales. They can be seen as long-term experiments in natural systems and with natural processes, which resemble those present in a waste repository. Such studies are very worthwhile for the following reasons:

1. to identify and understand geochemical processes and mechanisms which resemble those which may occur in, or in the vicinity of, a repository – and are consequently seen over realistically long periods
2. to produce results, which can be used to improve models based on laboratory data and the results of short-term field tests. The

possibility of comparing the waste repository to natural analogies plays an important role in supplying information to decision-makers and the general public.

Figure 5.2 Content of various radionuclides per ton of uranium at various times after removal from the reactor (Boiling water reactor fuel, degree of burn-up 50 MWd/kgU)



Source: M. Antilla. Radioactive Characteristics of the Spent Fuel of the Finnish Nuclear Power Plants. Working Report 2005-71, Posiva Oy, FI-27160 Olkiluoto, Finland).

Natural analogies consist of studies of uranium mineralizations, mining activity, geological “reactors”, archaeological and historical objects, old buildings, fallout from the testing of nuclear weapons and releases of radioactive substances from the destroyed Chernobyl reactor. This relevance refers as much to processes in the vicinity of the repository as to those further away.

Uranium mineralizations in e.g. Cigar Lake (Canada), Palmottu (Finland), Sierra Peña Blanca (Mexico) and Oklo (Gabon) have been used as natural analogies for repositories for spent nuclear fuel. The Oklo site in Gabon has also been found to be a prehistoric natural nuclear reactor and is therefore of special interest.

5.2 Oklo “reactors” and their “waste”

The so-called Oklo “reactors” are prehistoric natural “nuclear reactors” which have been active in Oklo, Gabon, west Africa for a long time. The “natural reactors” originated 2 billion years ago because the uranium concentration of the U-235 isotope, the most favourable isotope for nuclear fission, was 3.6% instead of 0.7% of the uranium as it is now. Such a high concentration is sufficient to produce a chain reaction of nuclear fission if there is uranium and water in sufficient quantities and no strong neutron-absorbing substances are present. During uranium mining in 1972 it was discovered that the U-235 concentration was lower (0.7171%) than normal (0.7202%) which was interpreted as meaning that U-235 had been consumed in some way. Afterwards, it could be pointed out that there was an occurrence of long-lived fission products. Subsequently, as the excavations and investigations proceeded, the geologists discovered a further 15 similar “reactors” in the area.

Over and above the 16 natural “reactors” in Oklo there is a “reactor” in Okélobondo which is an extension of the Oklo deposit and another one 35 km to the south in Bangombé. A typical reactor zone is around 10 m in diameter and around 50 cm thick.

All the “reactors” originated in places where a layer of uranium-bearing sandstone meets an overlying layer of clay-shale. Uranium was slowly concentrated in the boundary area since the oxygen-rich groundwater seeped up through the sandstone from below and brought the uranium with it. In the end, the amount of uranium was so large that the nuclear reaction became self-supporting exactly like in a nuclear power station.

A "reactor zone" may have been active for more than 100,000 years, perhaps up to a million years. The effect was low, a couple of hundred kilowatts. These long periods, however, meant that as much as six tons of U-235 were consumed and formed nearly an equivalent quantity of reaction products.

The reaction products are the same as in spent nuclear fuel. There are, for example, long-lived radioactive isotopes of the elements plutonium, strontium, caesium and krypton.

Investigations in the surroundings show that the plutonium has moved less than 3 m since it is rather quickly bound with the shale. The strontium is somewhat more mobile but has, nevertheless, remained close to the "reactor". It is probable that certain discharges of the more easily mobile elements caesium and krypton occurred to the surroundings. The uranium has practically not moved at all.

5.3 Other analogies

As already mentioned, there are a number of other natural analogies which may provide knowledge on how uranium, which constitutes the major part of the high-level waste, behaves in the natural environment.

5.3.1 Sierra Peña Blanca, Mexico

One place being investigated is a uranium deposit, Nopal I, in *Sierra Peña Blanca* near Chihuahua, Mexico. Natural uranite such as that in Nopal I is very similar to spent nuclear fuel in its composition and structure. The uranite deposit is mapped, its changes over time are monitored and investigations into the groundwater and its mineral content are carried out.

5.3.2 Cigar Lake, Canada

The same type of uranite deposit can be found in *Cigar Lake* in the northern part of the Province of Saskatchewan in Canada. It is estimated to be over 1,000 million years old and the mineralization seems to be one of the largest now known. Its depth (400–500 m) means that there is a groundwater flow, a groundwater composition (oxygen-poor water) and surrounding clay, which resemble the filling around the waste canisters in the Swedish programme. An important observation is that there is no trace of radioactive substances on the ground surface apart from those normally found there. The deposit was found by electromagnetic measurements, which showed that there was graphite in the bedrock. The geologists looked for graphite because where there is graphite there is also often uranium.

It is estimated that the uranium deposit was formed 1.3 billion years ago. It is 2 km long and between 50 and 100 m wide. The thickness varies between 1 and 20 m.

The uranium content in the ore is, on average 14%, but may locally reach as much as 55%.

There is a layer of clay around the ore body which is between 1 and 20 m thick and which effectively prohibits the radioactive substances from dispersing into the surroundings with groundwater flow. The ore body does not show any trace of radioactivity on the surface, which separates it from the natural background radiation. Yet the clay in Cigar Lake has, nevertheless, greater ability to conduct water than the bentonite layer in the final repository.

Contrary to the uranium deposit in Oklo, no natural radioactivity has ever taken place in Cigar Lake. There are too many substances, which absorb the free neutrons necessary to drive the nuclear fission process.

5.3.3 Palmottu, Finland

In the uranium mineralization in Nummi-Pusulu in *Palmottu* in western Nyland, Finland radioactive substances have been found to move extremely slowly within the rock. It is pointed out that at present it seems unlikely that any circumstances would arise which would mean that spent nuclear fuel could not be disposed of in the rock in a safe way.

5.3.4 Coles Hill, USA

There is also a very large uranium deposit in *Coles Hill*, Pittsylvania County in southern Virginia, USA. No uranium mining has ever taken place but the deposit has been carefully mapped with regard to geology, structure and geochemistry. Opportunities can be found here to further increase our knowledge of how the radioactive waste of today and tomorrow may be transported in bedrock.

5.4 Quantitative data concerning leaching of radioactive substances from uranium mineralizations and historical "reactors"

Investigation of the element technetium (Tc-99) at Cigar Lake and Oklo (Curtis 1996) can be mentioned as example of studies, which have been carried out.

At Cigar Lake Tc-99 is continually produced in measurable quantities through spontaneous fission in the massive uranium lumps. The discharge rate for Tc-99 during reducing groundwater conditions is estimated to be $1.1 \cdot 10^{-6}$ per year (i.e. 1 millionth of the content in a year). Through analyses of the element ruthenium (Ru-99) a study has been carried out at Oklo on how much Tc-99 was formed during the time when the "reactor" was active. It was found that about one third left the uranium while two-thirds were directly fixed. It is estimated that the discharge rate is $1.5 \cdot 10^{-6}$ per year, which is very similar to the value for Cigar Lake despite its other very disparate conditions.

5.5 Conclusions

Natural analogies can be of great help in understanding the different phenomena, which may arise in a final repository during the immensely long periods concerned. They also make it possible to test if the calculation models, which were used for making safety analyses for the deep repository, are realistic.

It is therefore urgent to continue and intensify the studies of natural analogies and to fully utilize the unique character of the natural reactors as well as the uranium mineralizations as a basis for the work on safety analyses.

6 Geological time perspectives

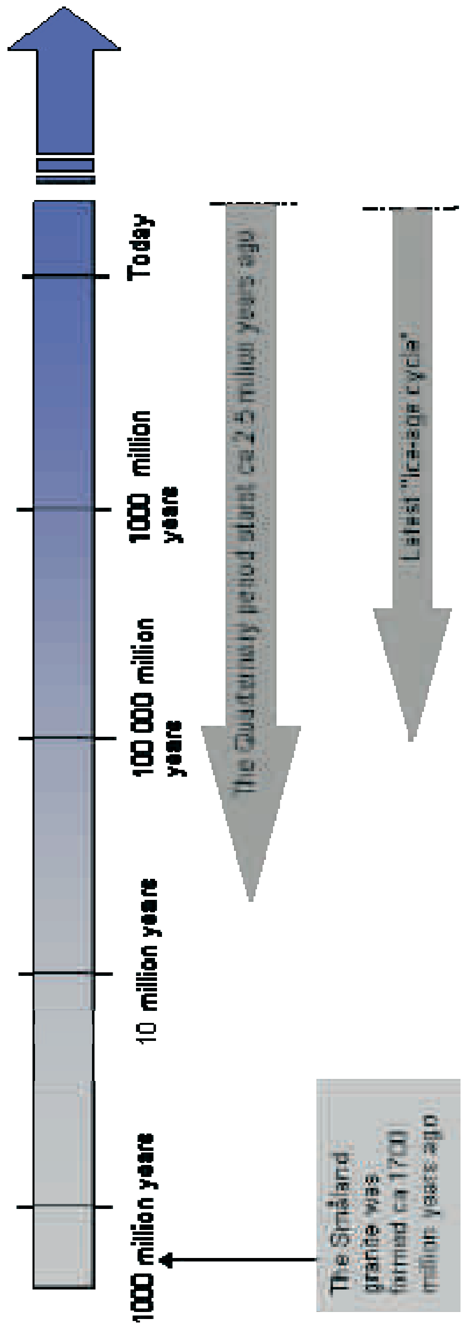
Gert Knutsson and Jimmy Stigh

6.1 Introduction

Geological history includes time perspectives of many different dimensions, from the formation of the oldest rock of the crystalline basement in the most northerly part of Sweden, unimaginably around 2.3 billion years ago, to the youngest lava beds from the latest eruption of Hekla in Iceland in 2000. Concerning unconsolidated deposits the time span is not so dizzying. However, the oldest land ice in Sweden deposited till ca. 250,000 years ago but River Klarälven its latest delta layer after this year's springtime flood. The groundwater in the deepest sandstone layers on the Kristianstad plain was formed during the Bronze Age, while the water in a small spring in till on the Linderödsåsen ridge to the south is only some months old.

The geological processes are thus often cyclical but with entirely different time horizons depending on the one hand on the type of process and on the other hand on the dimension. Certain processes work over a long time and produce very lasting results, e.g. the formation of crystalline rocks in the basement. Other processes are short-term and leave very little lasting impression for the future. Some of the processes may, however, be influenced by man through e.g. acidification of air, soils and water or emissions of greenhouse gases and consequently climate change. To understand the long-term disposal of nuclear waste these different processes and time perspectives must be observed. A time perspective of the different processes is illustrated in Figure 6.1.

Figure 6.1 Time perspectives of geological history



6.2 Geological time perspectives of the bedrock

A large step in the development of the concept of geological time was taken by the Scottish doctor James Hutton (1726-1797). Hutton developed the idea that the processes we observe in the rock mass today were also active when the rock was formed. The present is the key to the past. Geologists have worked to develop ways to classify and describe geological time. There is an endeavour to describe geological history in both relative and absolute age (dating). The relative age can be described by chronological events. An analogy is that if we put newspapers in a pile, the oldest newspaper will be at the bottom and they will then be in the order in which they were delivered. On certain days there are no newspapers but, nevertheless, the newspaper pile depicts the relative relationships between the newspapers when they are piled in succession. We can read the headlines and form a general understanding of what has happened. If we want to know the exact point of time we must look at the year and date of publication. This can be compared to an absolute dating. Geological methods of dating have developed rapidly over the last 25 years through the study of isotopes, and the dating of different rocks today is very reliable.

To understand geological time is very difficult since we constantly relate to historical time. One way is to try to think back to Roman times ca. 2,000 years ago when the aqueducts were constructed (see Figure 6.2).

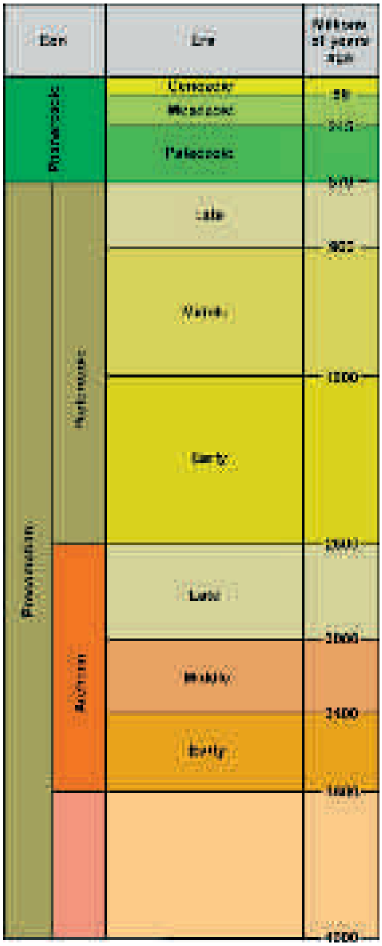
Figure 6.2 Aqueduct near Via Appia, Rome

The original water conduit, in the shape of a rectangular tunnel, was later supplemented with an open water conduit.
Source: Källor i Sverige (2006) p.111.

If we step back and try to understand all the events which have occurred from Roman times until today, we will discover that the periods covered describe an enormous number of great events. If we move from Roman times 2,000 years ago to 20,000 years ago it will be found that Sweden was covered by a large inland ice much the same as the land ice in Greenland. The ice melts away and plants, animals and man appear. If we move from 20,000 years to 100,000 years we can hardly, in our minds, keep up with it any longer. In 100,000 years however, the spent nuclear fuel will still be dangerous and must be safely disposed. From 100,000 to 1 million years is another large step. Geological time is often considered in millions of years.

The Earth is estimated to be 4,600 million years old and is divided into Precambrian with Archaean (4,600–2,500 million years ago), Proterozoic (2,500–570 million years ago) and Phanerozoic (570 million years ago until the present). See Figure 6.3.

Figure 6.3 The age of the Earth and its divisions

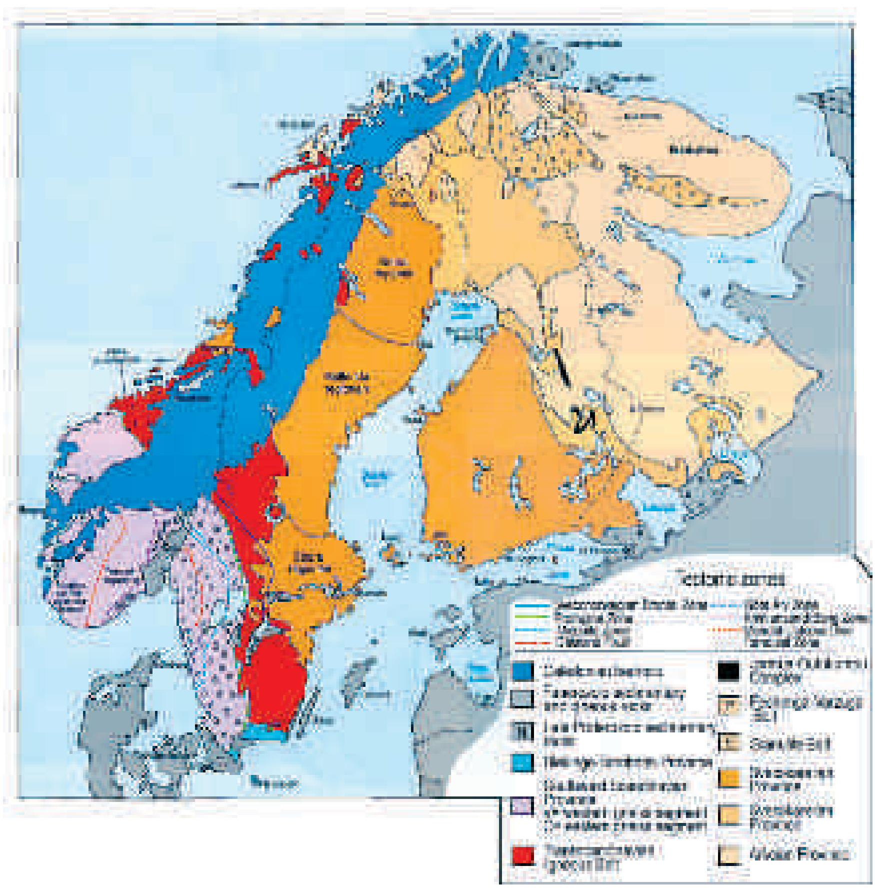


Source: KASAM's State-of-the-art report 2001 (SOU 2001:35 p. 102).

The transition between the time before Cambrian (Precambrian) and Cambrian (lower Paleozoic) occurred 570 million years ago. This boundary can be seen today in the Västgöta "mountains" where the crystalline basement is covered by the Cambrian sandstones. The crystalline rock here is, in itself, much older still and is estimated to be 1,700 million years old. Consequently younger parts of the basement have eroded away over more than a billion years. The boundary between the basement and the Cambrian sandstone represents more than a billion years of the Earth's history but this history cannot be recorded here. This period must be learnt about from other areas. In this way a picture may be formed of the geological history of the Earth through the study of the bedrock in Sweden and in the rest of the world. This assembled history is a basis for our knowledge of the Earth and its structure.

Sweden is dominated by rocks which were formed more than 1,500 million years ago (large parts of Precambrian). The bedrock and its different ages is schematically shown in Figure 6.4.

Figure 6.4 The bedrock of the Nordic countries and its age relationships

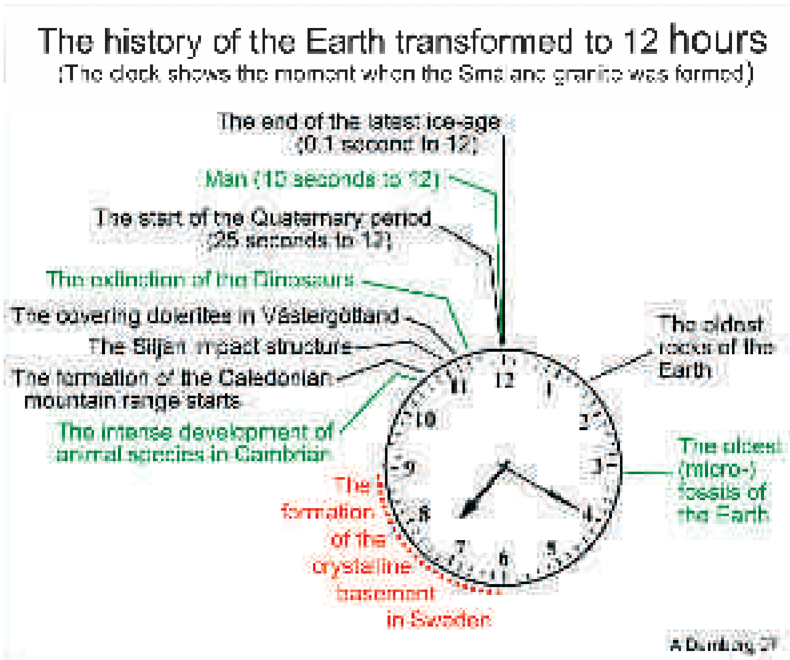


Source: KASAM's State-of-the-art report 2001 (SOU 2001:35 p. 101).

To get a picture of geological time, the age of the Earth (4,600 million years) can be transferred to the dial of a 12 hour clock. The Earth is formed and during the first two hours the atmosphere. About 01.30 a.m. the oldest known rock appears and about 03.00 a.m. the oldest fossil in the form of stromatolites (one-cell organisms). In Sweden the first known rock was formed immediately after 06.00 a.m. and other parts of the crystalline basement in Sweden up until 09.00 a.m. From about 06.00 a.m. until 10.30 a.m. the first ozone layer also developed and later the first supercontinent. Thereafter the ice-ages appeared and a large number of biological species became extinct.

From 10.30 a.m. until 12.00 noon (present time) species developed at a rapid rate but with large geological changes, e.g. orogenies; extinction of species also followed. This mass extinction occurred just before 11.00 a.m. and again about 11.30 a.m. when, for instance, the dinosaurs became extinct. The Quaternary period does not start before a bare half minute to 12.00 noon on the dial. Man's time on Earth cannot be shown on the hourly dial but must be shown in seconds. It may be said that humans have been here for the last 15 to 10 seconds and that they began to appear in Sweden 0.1 second before 12.00 noon (see Figure 6.5).

Figure 6.5 The history of the Earth transformed to 12 hours



Source: Mansfeld 2005, idea Jimmy Stigh, sketch by Anders Damberg 2007.

A bogglying thought with regard to time is for example. to look at the different minerals in the crystals of the Småland granite. These crystals were formed more than 1,700 million years ago and they are the same crystals which, after this inconceivable space of time, can still be held in our hands today (see Figure 6.6).

Figure 6.6 Detailed picture of the Småland granite

Source: SGU's archive. Photo Anders Damberg, 2007.

The geological history of Sweden seen in the perspective of a repository for spent nuclear fuel is described in more detail in KASAM's State-of-the-art report 2001 (SOU 2001:35 pp.95-112).

6.3 Quaternary time perspectives

The Quaternary period is the youngest of the geological periods and covers ca. 2.5 million years in its entirety. It is, however, only the last 100,000 years "ice-age cycle" which is relatively well known in Sweden with regard to changes in climate, landscape and water levels and time events. It is therefore possible to understand what may happen during a conceivable ice-age cycle within the next 100,000 years, and this is relevant for the storage of nuclear waste. A very brief account is given below of the development over the whole period and its causes; thereafter a more in-depth account is given of what happened during the latest ice-age and later.

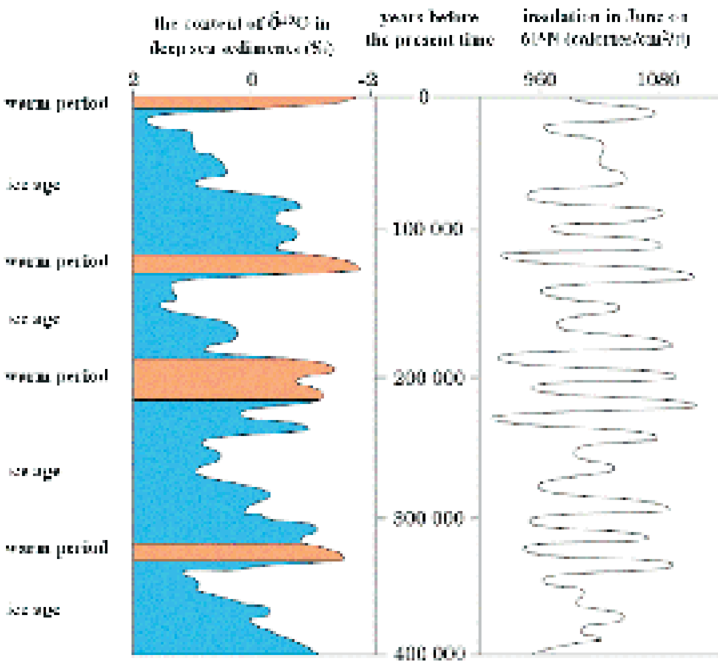
6.3.1 The Quaternary in its entirety

Nowadays the Quaternary period is considered to have started between 2 and 3 million years ago; at the time the average temperature decreased sharply. The first large land ice originated in, among others, northern Europe ca. 2.7 million years ago but somewhat later in other parts of the world which is why the global boundary for the Quaternary period is considered to be 2.5 million years ago. It is characterised in its entirety by a moderately cold climate but with large relatively regular changes between the ice-ages (glacial periods) and warm periods (inter-glacial periods). During the last part of the Quaternary period there is evidence of up to eight ice-ages with a duration of ca. 100,000 years each and intermediary warm periods of 10,000-20,000 years each (National Encyclopaedia 1993). The climate during the warm periods was at least as mild as it is today and the vegetation similar in character. In Scandinavia there are definite traces of three ice-ages and four warm periods but it is likely that considerably more have occurred. The penultimate ice-age was the most extensive and was followed by a short warm period of a good 10,000 years.

The major climate change at the beginning of the Quaternary period was probably due, in large measure, to geographical changes such as orogenic uplifts and other tectonic phenomena which influenced the circulation in the atmosphere (and initiated glaciation) as well as a change in the ocean currents, for example the Gulf Stream, most of all in the Arctic seas. For a land ice to be formed and further develop a decrease in temperature of ca. 5° C is needed and a considerable accumulation of snow from year to year so that a glacier is formed in a highland area. Snow and ice masses reflect more of the incoming sunlight than bare ground, whereby the climate gradually becomes colder, the glacier extends over low-lying land areas and transforms into a land ice.

The changes between ice-ages and warm periods are caused mostly by astronomical factors with different time cycles which control insolation to the Earth. It is, above all, changes in the Earth's orbit from nearly round to more elliptical (100,000 years cycle), tilting of the Earth's axis (41,000 year cycle) and turning of the Earth's axis which influence insolation distribution – interacting with the changes in the shape of the Earth's orbit – during different periods (23,000–19,000 year cycle) (National Encyclopaedia 1993). These factors influence each other and result in variations in the insolation (Figure 6.7). During the last part of the Quaternary period the 100,000 year cycle has been predominant. Changes in insolation intensity and global changes in the composition of the atmosphere are other active factors which are influenced among others by volcanic eruptions.

Figure 6.7 Changes between warm periods and ice-ages and insolation intensity



Source: National Encyclopaedia, volume 10, p.3 (1993).

Changes between the ice-ages and warm periods have, of course, also meant that the volume of salt water – and with that the shorelines in coastal areas – changed many times during the Quaternary period. It has been estimated that between 5% and 6% of all water on Earth was stored in land ice during its maximum extension. From time to time large shallow sea areas dried out. However, because of the enormous weight of the land ice (3 kms thickness) the Earth's crust was depressed, which meant that large coastal areas were inundated when the land ice melted but later dried out again when the Earth's crust slowly regained its original position, the so-called land uplift.

Above all, clarification of changes in temperature as well as in water volumes have been possible by measurement of the relationships between the stable oxygen isotopes O-18 and O-16 in the shells of micro-fossils (foraminifera) in deep sea sediments. The relationship between O-18 and O-16 provides information about the temperature of sea water and how much water is stored in land ice (Figure 6.7). The oxygen isotope method has also been used for investigations of deep drill cores from the land ice on Greenland and Antarctica so as to obtain a direct measurement of the temperature changes during the last part of the Quaternary period. The investigations show that the changes over the last 50,000 years have been extensive as well as rapid but, unexpectedly enough, opposed to each other in these two areas, the so-called seesaw effect (Rundgren and Björk 2007).

6.3.2 The latest part of the Quaternary period – at least 100,000 ago

The latest part of the Quaternary period started ca. 115,000 years ago with a complex ice-age (Weichsel) which finished ca. 12,000 years ago, when the present warm period (Holocene) started.

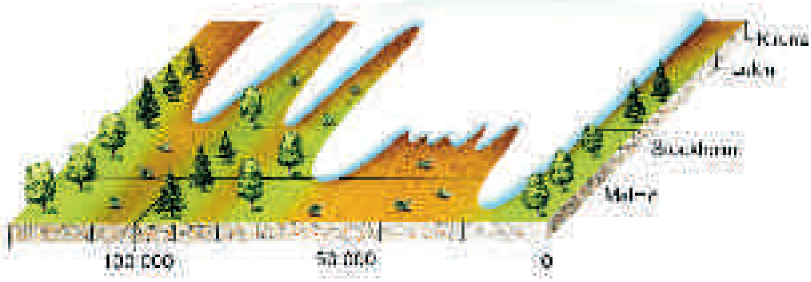
There are several relatively reliable methods available to determine the age of the latest part of the Quaternary period. There are two types: relative and absolute methods. With the relative methods the internal age relationships between different layers at a certain site are clarified. This can be done principally with the help of fossils, for example. pollen, which may be compared with and perhaps agree with fossil information from other sites. The "absolute" methods aim to give the direct age of a layer or a fossil.

The oldest “absolute” method, *varve chronology*, was developed in Sweden at the end of the 1800s by Gerhard De Geer, who in 1912 presented a time scale (over 12,000 years) for the latest deglaciation of the land ice from Skåne (Scania)to Norrland. The method was based on the fact that each year a varve of clay was formed during deglaciation. Measurements of a clay stratigraphy in a certain place often provide a characteristic diagram on the basis of changes in the thickness of the varve which reflects changes in climate, melt water flow and sediment transport. This makes it possible to link together the diagram from one place with a typical part of a diagram of the varves in another place, located further north and consequently nearer the melting land ice.

However, the method has a certain unreliability and is no longer regarded as an “absolute” method unlike later developed radiometric dating methods, principally *the carbon-14 method*. This method is based on the fact that living organisms absorb carbon from the carbon dioxide in the atmosphere with a small portion of the radioactive isotope C-14. When the organism dies, the intake of carbon ceases and C-14 starts to decay with a known half-time. Theoretically, one can date organic material up to 60,000–70,000 years old. However, since the production of carbon dioxide in the atmosphere has varied, and other sources of error are large at very low concentrations, dating has often been limited to ca. 20,000 years. Another absolute dating method is to measure the yearly growth rings in very old living trees and fossil tree trunks (dendrochronology). With this method it is possible to go back 12,000 years in Central Europe. Therefore dendrochronology is used to calibrate the carbon-14 method (Lindström et al., 2000).

As mentioned, the latest ice-age was a complex process with changes between colder so-called stadials, when the land ice advanced and warmer so-called interstadials, when the land ice melted. At least three stadials with land ice over parts of, or the entire Nordic region, have been differentiated with intermediary, almost ice-free interstadials (see Figure 6.8).

Figure 6.8 Climate change during the latest ice-age cycle



Source: Wallroth 1997 (SKB report R-97-11 p. 9).

These stadials may have been caused by the shorter astronomical cycles (see above). It is also interesting that the land ice increased gradually in size and length. The last stadial had the largest extension and length. It started ca. 70,000 years ago, when the glaciers in the mountain range expanded to form land ice which gradually covered large parts of the Nordic region. The coastal areas in western Norway, Denmark and Sweden, like the most southerly part of Sweden, were, however, probably ice-free over shorter periods with somewhat milder climate. The land ice reached its maximum extension as late as 22,000-18,000 years ago (Andréasson 2006 p.431). At that time its centre was far east of the mountain range, perhaps out over the Gulf of Bothnia, and its southern limit was around present-day Berlin. It is interesting, in this context, that due to high precipitation and snow accumulation in the margin of the land ice in the southern Baltic, local ice centres, ice domes, may have formed from which the ice moved in different directions. This would explain the complicated till deposits in Skåne (Lagerlund 1987). The extension of the lastest ice-age is illustrated in Figure 6.9

Figure 6.9 Maximum extension of the land ice in Europe during the latest ice-age

The land area which lies below sea level today is marked in green.
Source: Heijkenskjöld (1988) p. 53.

Deglaciation of the land ice began 18,000 years ago and was caused by a marked improvement in the climate. The first deglaciated part of Sweden was north-western Skåne ca. 16,000 years ago. The deglaciation period was characterised by rapid changes in temperature with three colder, so-called Dryas stadials (named after the mountain flower *Dryas octopetala*) and two warmer interstadial periods. During the Dryas stadials deglaciation ceased and the land ice even advanced whereby large marginal deposits of till and glaciofluvial sediments were formed. The most significant marginal deposits during the very cold Younger Dryas stadial can be followed as a stretch of deposits from southern Norway across south central Sweden to southern Finland. Thereafter there was a major temperature increase which caused a very rapid melting of the land ice. This point in time, ca. 12,000 years ago, is therefore defined as the end of the lastest ice-age and the beginning of the present warm period. It is estimated that the land ice vanished entirely

8,500 years ago – possibly local glaciers may still have existed in the highest mountains (Lindström et al., 2000).

6.3.3 Changes in the landscape during and after the latest ice-age

The formation and extension of the land ice implied large changes in rock, soil and water, both beneath and outside the land ice. As a matter of fact the extending land ice was plastic and advanced slowly, but in the beginning its bottom layer was cold which meant that the groundwater froze to ice. This led to the widening of fractures and pores in the rock and to the termination of recharge as well as flow of groundwater. Later, as the land ice became thicker, the pressure on the bottom layer became so great that it began to melt. Part of the meltwater from the surface also found its way into the crevasses in the ice. In this way the groundwater recharge recommenced and there was a groundwater flow towards the margin of the ice. However, outside this the groundwater flow was forced down to great depths. The landscape outside the land ice was characterised by permanently frozen ground (permafrost) and tundra. During glaciation the permafrost had formed over a long period of different phases and thereby to great depths (several hundred meters). Consequently, this meant that the ground contained large volumes of frozen and immobile groundwater, which acted as a tight cover and the recharge of groundwater was greatly reduced or stopped entirely. The composition of the groundwater was also influenced since the salts in the groundwater "froze out" and were added to the liquid groundwater. The permafrost also meant that frost cracks were formed in the superficial parts and that the rock pressure increased, which enlarged the fractures in the rock.

However, the large-scale change in the rock was caused by the great weight of the land ice. The outcome was that the Earth's crust was pressed down elastically and also that the Earth's crust outside the land ice "oozed up". The greatest depression occurred in the central parts of the so-called ice divide. But the land ice and the periodically high water pressure also influenced the current rock stresses, above all, increased the vertical stress. Changed stress relationships caused existing rock fractures to react in different ways – some of them opened, some closed – which in its turn influenced the permeability of the rock in different directions. Certain fractures, which are considered to have arisen through so-called hydraulic fracturing, can now be observed as sediment-filled fractures in the superficial part of the rock, for example in Forsmark (KASAM 2004 p.177). The very high water pressure at the ice margin may also have contributed to the formation of new fractures.

The movement of the land ice from its centre meant that the ice usually brought unconsolidated deposits and weathering material from the underlaying beds, polished the bedrock on the stoss side and plucked away loose boulders and stones from the leeside. In other words the land ice eroded the ground surface and created the material for its most typical deposit, the till. In the initial phase of land ice with glacier tongues the erosion was great in the mountain valleys whereby so-called U-valleys were formed and even over-deepened, e.g. in the Swedish lakes along the mountain fringe (Hornavan 221 m deep, Torneträsk 168 m deep) and in the Norwegian fjords. On the other hand, the erosion seems to have been very modest or non-existent in other areas, especially during certain cold spells in the latest land ice phase. As a matter of fact weathered rock material still remains as well as older moraine formations and till-covered loose deposits, above all in northern Skåne (weathered rock), central and eastern Småland and in the inner part of Norrland (Lokrantz and Sohlenius 2006). Some deposits in Norrland derived from the first land ice stadial and a dark, clayey till, which is found in sheltered locations right down to the Mälardalen valley, are thought to be from the second land ice stadial (Lindström et al., 2000). There is probably a great deal of information of this type hidden under later deposits.

The land ice deposits are made up of, in the strict sense of the word, different types of till which are estimated to cover three quarters of Sweden's bedrock surface and are thereby the most common type of overburden in the country. The till consists of material picked up by the ice which is mixed, crushed and ground during shorter or longer transport in the land ice. The longer it is transported the more it is ground down, how much depends on the hardness of the rock material. Soft rock such as shale and limestone gave rise to a high clay content and clayey till like e.g. the clay till in Skåne and clayey till in certain parts of Uppland; hard rock such as quartzite and porphyry on the other hand, to a stoney, gravelly till, which is found in the inner part of eastern Småland and in northern Dalarna and Härjedalen. While the land ice was moving a layer of hard-packed and tight, so-called bottom till, some meters thick, was deposited, which here and there also created special land forms, for example elongated drumlins. In conjunction with occasional or annual ice advance the land ice pushed together ridges of till, so-called end moraines and with great advances, so-called terminal moraines (see below). During the final rapid deglaciation on land large quantities of ice were often cut off from the active ice, for example by hilly areas. The remaining material was deposited in this "dead ice" in the form of irregular hills with a loosely packed till, which often contained lenses of water-sorted sand from small meltwater flows, thus a more permeable soil.

Rapid deglaciation of the land ice also meant that the Earth's crust was suddenly relieved of the stress from the pressure of the land ice which caused the frequency of earthquakes to increase. Movements in the Earth's crust in the form of faults have also been documented in several places in northern Scandinavia where deglaciation was especially rapid and possibly also further south (KASAM 2004 p.192).

Large volumes of meltwater gathered in tunnels or channels in the land ice as glaciofluvial rivers which brought with them much material which was rounded during the transport and was sorted when it settled near the ice margin in the form of gravel eskers or directly outside the ice margin as sand deltas or fine-grained outwash plains. In these large deposits the most significant groundwater reservoirs are formed, which are of great importance for the supply of drinking water in Sweden. Outside the land ice more fine-grained deposits of fine sand, silt and clay were formed, which now constitute plains for agriculture or fill deep valleys.

The large volumes of meltwater also led to extensive groundwater recharge in underlying layers of unconsolidated deposits and bedrock. The large water pressure from water bodies higher up in the still thick land ice caused the recharge of oxygenated water deep down to the bedrock. There are traces of this so-called meteoritic water at depths of ca. 1,000 m in Sweden and at ca. 2,000 m or even more in the Kola peninsula (Smellie 2004).

6.3.4 Changes in seas and lakes during and after the latest ice-age

The glaciation effects on the changes of the volume of water in the sea and on the shoreline have already been touched upon briefly. During the lastest ice-age when the land ice was most extensive, the sea level was 100–120 m below its present level. At the same time the Earth's crust was depressed at least 800 m below the central parts of the land ice, but with decreasing values towards the south and the north. When the land ice began to melt 18,000 years ago the surrounding sea received considerable volumes of meltwater, whereby the sea level rose, a so-called eustatic rise. At the same time the pressure of the land ice on the Earth's crust was reduced and it slowly started to regain its previous level, a so-called isostatic uplift or land uplift (least in the south). A complicated interaction arose between these two processes as well as with melting land ice towards the north and with surrounding land and sea areas. In certain places ice lakes dammed by ice arose, e.g. in the south Swedish highlands and in the inner part of Norrland.

The process in the Baltic basin became especially complicated since, moreover, shifts between fresh, salt and brackish water took place. First a large lake dammed by ice was formed, the Baltic Ice Lake with an outlet to the south-west through the Öresund area. This became shallow through land uplift whereby the outlet moved to the south-central Swedish lowlands. After certain reorientations in connection with the advance of the land ice during the Younger Dryas stadial, the level gradually coincided with the level of the Ocean and a short salt water stage, the Yoldia Sea, began ca. 11,600 years ago (Björk 2002). The land uplift then took over and after ca. 1,000 years the Baltic became a freshwater lake, called the Ancylus Lake, which initially had an outlet to the west among others through the Göta river valley. The increasing land uplift in the north meant, however, that the straits in the west dried up and the water in the Ancylus Lake began to be displaced southwards with a consequential shoreline rise and connection with the Ocean through the Large Belt strait (Stora Bält) in Denmark. During a transition period 10,000-8,500 before the present time, there was a small inflow of brackish water through the Danish straits. At the end of this phase large parts of the land ice had melted which caused a major rise in the sea level so that salt water flowed in through the Danish straits and the Öresund strait. This introduced a relatively salt phase, the Littorina Sea, which arose in the Baltic basin ca. 8,500 years ago. This led to a rise of the shoreline in the southern part of the basin and on the west coast where the rise was larger than the land uplift. This described development is illustrated in Figure 6.10. During Littorina time the average temperature was also a couple of degrees higher than at present. The average temperature began to decrease ca. 5,000 years ago and reached its lowest value during the so-called "Small ice-age" (Lilla istiden) in the 1500s–1700s which among others enabled Swedish troops in a war to cross the ice-covered Danish straits in 1658.

Figure 6.10 The major stages in the development of the Baltic basin during and after the latest ice-age

Source: Geology (National Atlas of Sweden 1994, pp. 138-141).

The shoreline shift is also the result of an interaction between the above-mentioned processes and terrain conditions. The highest coastline in the southern Baltic basin was formed during the Baltic Ice Lake stage. Due to the disproportionate land uplift the values for the highest coastline are lowest in the south where they are near the present coastline while they are about 100 m.a.s.l. in the northern part of the municipality of Oskarshamn and about 200 m.a.s.l. west of Gävle. The values rise successively towards the north and reach the highest value, 285 m.a.s.l. in Skuleskogen, Ångermanland, after which the values decrease northwards to about 200 m.a.s.l. north-west of Luleå. Local deviations exist however (KASAM 2004 pp. 196–197).

Since then there has been a predominant lowering of the coastline caused by continued large land uplift in the coastal areas from northern Svealand and the whole of Norrland. It is important to note that in the area south of it there have been shoreline rises during certain earlier stages of the Baltic Sea, some of which with relatively salt water. This has influenced the groundwater chemistry in coastal areas, for example. the area of Oskarshamn which has been analysed in detail with the help of hydrochemical modelling in combination with Quaternary geological data (Figures 6.11).

Figure 6.11a Conceptual model of different events in geological development since the ice-age which have influenced the groundwater chemistry at Äspö

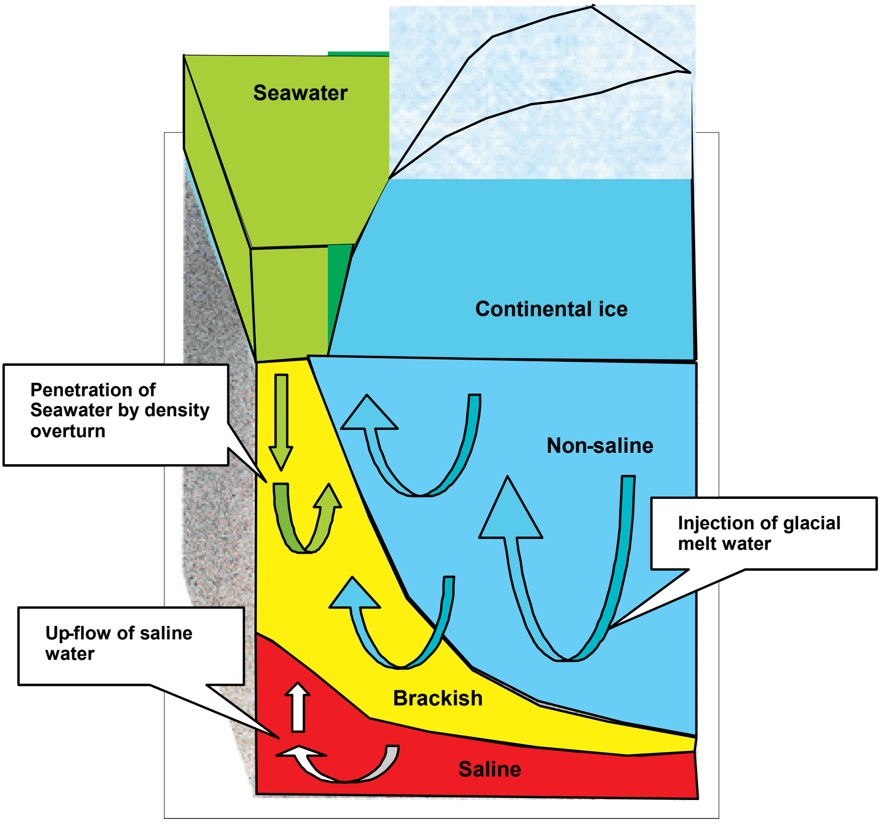
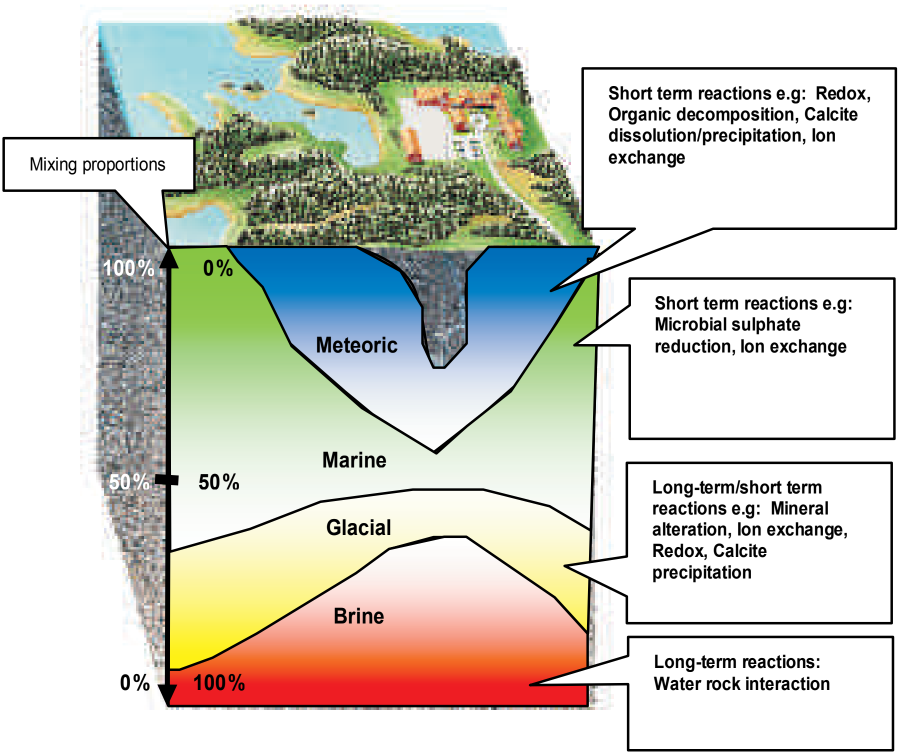


Figure 6.11b Calculation of mixing proportions of different types of water at Äspö and predominant mass-balance reactions with the help of the so called M-3 model (from Laaksoharju, 1999 in Knutsson & Morfeldt 2002)



Source: KASAM's State-of-the-art report 2004 (SOU 2004:67pp. 257-258).

6.3.5 Summary

The Quaternary period covers ca. 2.5 million years and is characterised by a rather cold climate with large relatively regular changes between ice-ages and warm periods. These changes are caused mainly by astronomical factors with different time cycles which control insolation to the Earth and which influence each other which results in variations in insolation at typical intervals of time. The 100,000 year cycle has been predominant during the latest part of the Quaternary period. During the same period there is proof of eight ice- ages with a duration of ca. 100,000 years each and intermediary warm periods of 10,000–20,000 years each; in Scandinavia there are definite traces of three ice-ages and four warm periods.

It is, however, only the latest "ice-age cycle" which is relatively well known as regards changes in climate, landscape and water levels. It began ca. 115,000 years ago and finished ca. 12,000 years ago when the present warm period started. The ice-age cycle was a complex process with changes between colder so-called stadials (at least three), when the land ice advanced and warmer so-called interstadials, when the land ice melted. The latest stadial began ca. 70,000 years ago and the land ice had its largest extension ca. 20,000 years ago, when it covered the major part of the Nordic region with the southern limit around present-day Berlin. The melting of the land ice began 18,000 years ago because of a marked improvement in the climate. The deglaciation is characterised by rapid temperature changes but after a very cold stadial when the ice margin was over south central Sweden a major temperature increase followed ca. 12,000 years ago, which meant a very rapid deglaciation of the land ice. This point in time therefore is judged to be the end of the latest ice-age. It is estimated that the land ice had totally vanished ca. 8,500 years ago.

The changes in the landscape during and after the latest ice-age were very extensive. The Earth's crust was depressed elastically roughly 800 m beneath the central parts of the land ice. Through the weight of the ice and the periodically high water pressure the rock stresses also increased, especially the vertical stress which influenced the formation of fractures and permeability in the rock. Initially the groundwater was frozen under the cold land ice but when it grew thicker and started to melt, groundwater recharge could take place and flow started towards the ice margin. There were, however, also large areas with permanently frozen ground (permafrost) at great depths, which forced groundwater flow from the land ice down to under the level where the local groundwater was frozen and groundwater recharge more or less not present. The permafrost also meant that frost cracks formed in the superficial parts and the rock pressure increased which widened the fractures in the rock.

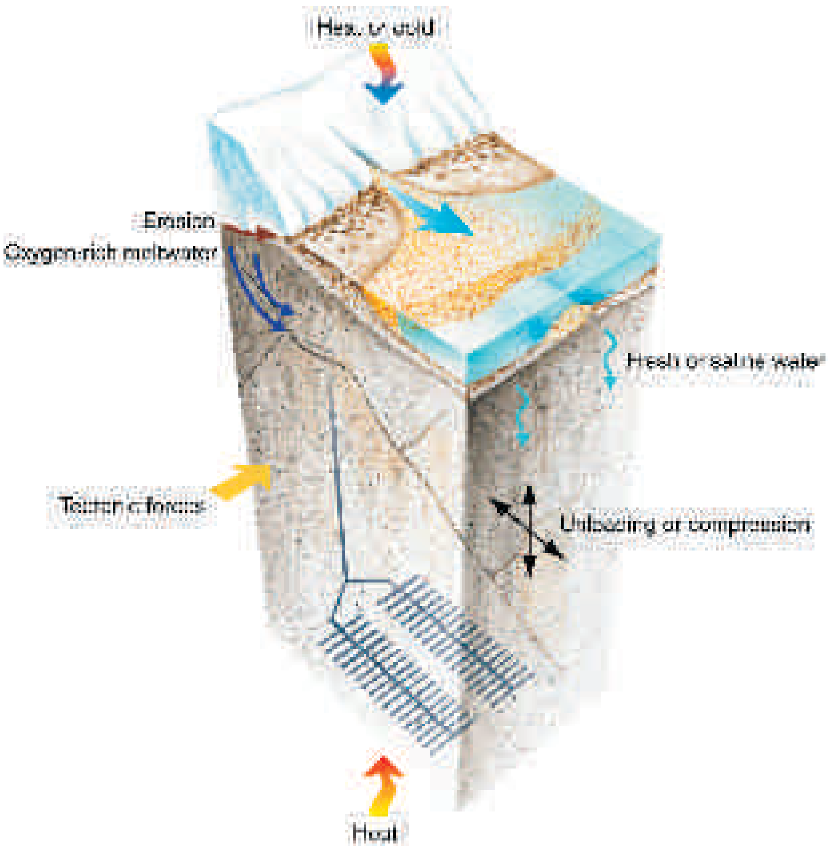
The movement of the land ice from the ice divide towards the ice margin meant that the ice took up unconsolidated deposits and weathered material from the underlyaying beds, polished and broke up the rock, crushed and mixed the different materials to its most typical deposit, till, which is estimated to cover approximately three-quarters of Sweden's bedrock surface. When the land ice melted, glaciofluvial rivers were formed which transported, washed out and sorted material from the land ice and deposited the material in the shape of gravel eskers, sand deltas and clay plains. The large volumes of meltwater also involved extensive groundwater recharge in the underlying layers. The great water pressure from the thick land ice above led to the recharge of oxygenated water down to a couple of thousand meters in the bedrock.

The changes in lakes and seas were also very extensive. When the land ice was at its most extensive and thickest state and bound up large volumes of water, sea levels were 100–120 m below the present level and at the same time the Earth's crust was depressed. When deglaciation began the sea again received large volumes of water whereby the sea level rose relatively quickly. The sudden relief on the Earth's crust caused earthquakes and faults, at least in northern Sweden. But the Earth's crust slowly regained its position, the so-called land uplift. A complicated interchange took place between this process and the rise in the sea level and the melting land ice towards the north and surrounding land and sea areas. The process in the Baltic basin became especially complicated since there were moreover shifts between fresh, salt and brackish water over five different phases. The displacement of the shoreline is also the result of the above-mentioned processes and terrain conditions. To the extreme south the highest coastline is close to the present one, in the northern part of the municipality of Oskarshamn it is about 100 m.a.s.l., west of Gävle about 200 m.a.s.l., while it reaches its highest value 285 m.a.s.l. in Ångermanland, north of which it decreases to about 200 m.a.s.l. north-west of Luleå. In southern and south central Sweden the coastal areas and their groundwaters were influenced by the shifting levels and salt concentrations in the Baltic basin, by which different types of "mixed waters" arose.

Thus glaciation has a great impact on unconsolidated deposits, bedrock and water also at great depth. Changes take place over a long time and their essential features are probably repeated even in a conceivable new ice-age. There is therefore every reason to carefully analyse the processes of events during past ice-ages to be able to judge what consequences a new ice-age may have for a nuclear waste repository.

The following principal sketch (Figure 6.12) summarises in a clear way some essential processes which may influence the geological and hydrological conditions in a final repository of the KBS-3 type.

Figure 6.12 Possible influences in a 100,000 year perspective on the rock mass within which a deep repository will be placed



Source: After Wallroth 1997 (SKB report R-97-11 p.5)

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7 Future climate development

Bert Bolin

7.1 Some introductory comments

It has been known for many decades that the Quaternary period has been characterised by rather regular changes between ice-ages and warm periods (interglacials), which recurred in intervals of 100,000 to 130,000 years over ca. 2½ million years. This knowledge is based on observations of the stratigraphy of deep sea sediments and ice samples from the inland ice in Greenland and in Antarctica and a series of other observations on changes in nature. Section 6.3 contains a more detailed description of what we know about these changes today and in particular the extensive changes which took place in the Nordic region when the latest ice-age disappeared 10,000 to 15,000 years ago.

More specific studies to try to answer the central question if and when a new ice-age might be expected began 30–40 years ago (see e.g. Kukla and Kukla, 1972). On the basis of analyses of the duration of the latest interglacials (ca. 10,000 years), some experts advocated that a new ice-age was perhaps rather imminent. Others asserted that man's emissions of greenhouse gases and a gradual warming of the Earth would perhaps instead postpone a new ice-age, but attempts to analyse this question in more detail have been put aside. The following chapter will clarify these central questions and answer them on the basis of theoretical calculations with the help of climate models which have been developed primarily to try to understand the causes of the ongoing climate change. They are now, however, also of further use in the study of possible natural future climate change in the longer term (Berger et al., 2003, IPCC 2007, chapters 10.6 and 10.7). It is obvious however that it is not possible to describe future changes with the same detailed knowledge as we have today of the latest melting of the Scandinavian inland ice.

It is helpful to differentiate between three separate time-scales in the following discussion:

- Climate change in the 1900's and 2000's, principally caused by man, and above all with attention to alternative scenarios in an attempt to stem change during the next half century to reach long-term sustainable development on Earth
- The following ca. 1,000 years and, in particular, the consequences of the considerable disturbance which the global climate system has now been subjected to and will be subjected to over the next several hundred years
- The following ca. 100,000 years, when climate variations, as far as one can judge, will again, primarily, be decided by astronomically controlled variations of insolation. It cannot be excluded however that on this time-scale the climate may also be influenced by a lingering reinforced greenhouse effect to a certain degree.

7.2 Alternative development scenarios over the next hundred years

The magnitude of the incoming insolation and its variations from season to season, as well as its distribution over the Earth, does not change appreciably over one or two hundred years and it is predicted that it will not play anything more than a marginal role in the studies which have been made of the ongoing climate change and its further development in the present century. There is an abundance of literature on a great number of scenarios which have been calculated with the help of climate models and which serve as a basis for our present knowledge of the dynamics of the ongoing climate change. This report is restricted to the most important conclusions which have recently been summarised in IPCC's fourth evaluation report, Assessment Report No. 4, AR4 (IPCC, 2007) and which are of interest in a longer time perspective. AR4, which is based on three previous evaluations and new research results during the first six years of the 21^{st} century confirms all essential earlier conclusions which, of course, increases its credibility (IPCC, 2001; IPCC, 1996; IPCC, 1990).

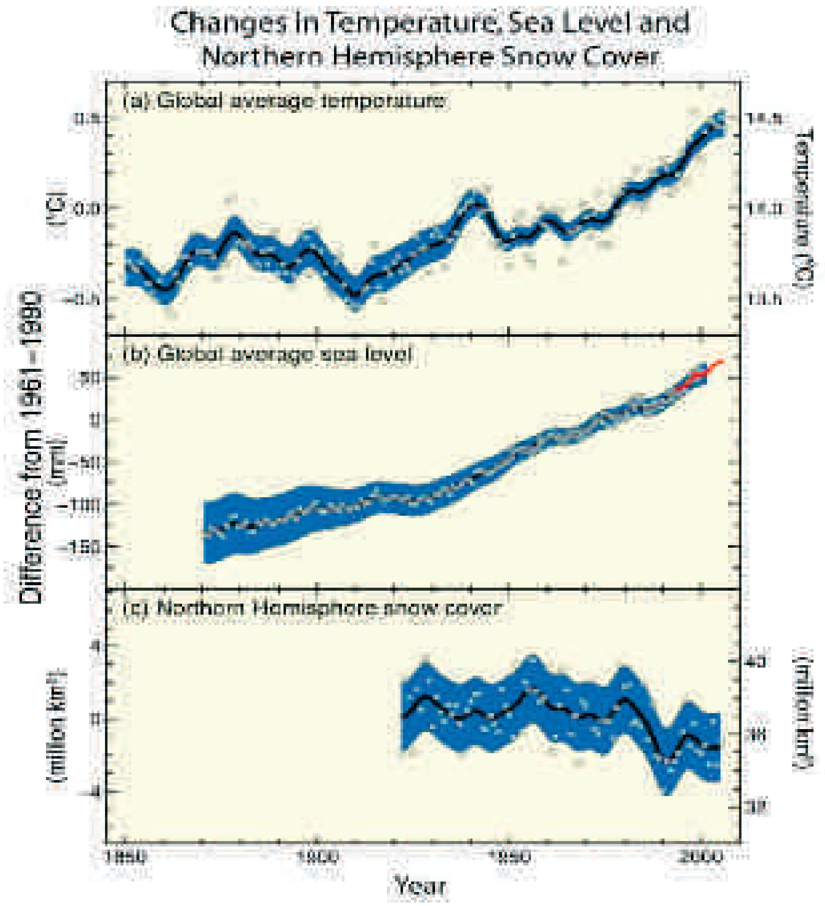
Above all the report underlines that the totally overwhelming part of research society now considers that it is very likely that most of the warming which has been observed over the last ca. 50 years is caused by man's emissions of greenhouse gases. Yet a report from IPCC in 1996 expressed significant uncertainties about the question of man's role, but the current report AR4 shows irrefutably what was only suspected ten years ago. The figure below, Figure 7.1, illustrates the changes in some important parameters.

Some further central conclusions:

- The global average temperature has increased by 0.8±0.2°C from the end of the 1800's up to 2006 (Figure 7.1), on average by nearly 1.0°C on land and almost around 0.7°C at sea. The temperature increase has been greater over the North Pole area and bordering land areas than on lower latitudes. It has increased more in the northern themisphere than in the southern.
- The water level of the oceans has risen by ca. 20 cm from 1870 until now and the extension of the snow cover around the northern arctic areas in March-April, has decreased by about 4 million km^2 (around 10%) since 1920 (cf. Figure 7.1).
- It is, above all, the emissions of carbon dioxide (CO_2) which are the most important cause of the ongoing warming, but methane, nitrous oxide and a series of other greenhouse gases together contribute to around ⅓ of the total reinforced greenhouse effect. This is counteracted, on the other hand, by smoke and dust particles (aerosols) which are also emitted by man.
- The total emissions of greenhouse gases into the atmosphere up until present (2006) have led to an increase in carbon dioxide concentrations from 280 (around 200 years ago) to about 380 ppmv[1]. Their combined reinforcement of the greenhouse effect corresponds to an increase in carbon dioxide concentration to around 440 ppmv, i.e. an increase of around 55%.
- The climate system is sluggish, above all because of the large quantity of heat which is required to heat up the ocean. That means that we still cannot record more than perhaps ½ to ⅔ of the global warming which the emissions so far of greenhouse gases and aerosols will gradually lead to.

[1]ppmv = parts per million (volume).

Figure 7.1 **Observed changes of (a) global average surface temperature (b) global average sea level according to measurements with water gauges (blue) and satellites (red) (c) the extension of snow cover in the northern hemisphere in March/April. All changes are given in relation to comparable averages for the period 1961–1990.**



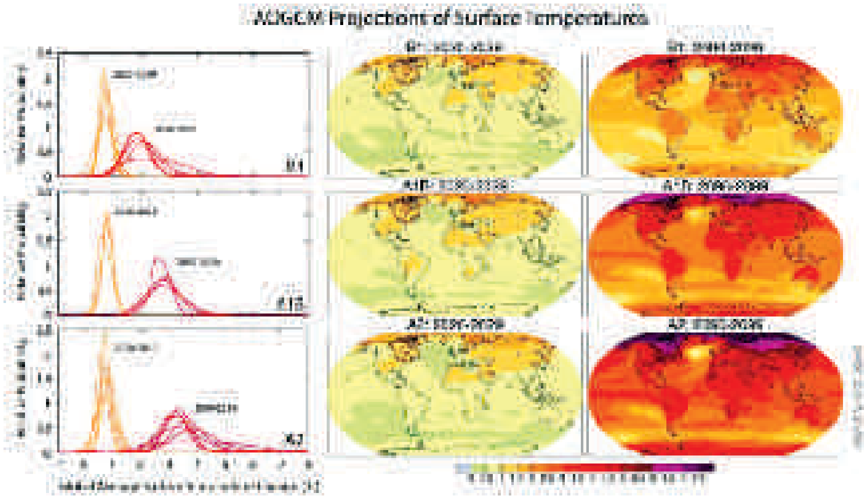
Source: IPCC (2007).

- It is also probable that precipitation will increase in the higher latitudes, which already has been seen to be the case in the northern parts of Scandinavia, while increased risk for drought is expected on latitudes 30°-50°, for example in the Mediterranean area. In general, the risk for drought will increase in arid areas and the risk for greater precipitation will increase where the climate is already humid.

A change of climate will, of course, influence surface run-off and the recharge of groundwater as well as vegetation conditions on Earth. The possibilities of re-establishing deciduous forests will thus probably increase in southern Scandinavia and the timber line will move northwards and to higher elevations in the mountainous areas.

It is time-consuming and still politically controversial to change the global energy system to the use of non-fossil-fuel-based primary energy. One of the reasons for this is the obvious ambition of developing countries to gradually catch up with the industrial countries in their economic development. It will therefore be difficult to stem the increase of the reinforced greenhouse effect and reach stabilization at a lower level than what would be a doubling of the CO_2 concentration from the early 1800's i.e. to around 560 ppmv. Added to this is the influence of other greenhouse gases the concentration of which is slowly increasing. Thus it is calculated that the global temperature will increase by around 2½°C until the turn of the next century which means that the ambition of the European Union in 1998 that the global temperature rise since the end of the 1800's should be limited to +2°C will probably not be realised. It is probable that also in the future warming will be greater over the Arctic Ocean than in lower latitudes which may imply a nearly ice-free Arctic Ocean during a shorter period in the late summers already towards the end of this century. For an illustration of these views reference is made to Figure 7.2.

Figure 7.2 Projections of changes of global average temperature up to the beginning 2020`s and the 2090`s compared to conditions 1980-1999.



Source: IPCC (2007).

The pictures in the middle and to the right show average projections according to the Atmosphere Ocean General Circulation multi-Model (AOGCM) for scenarios B1 (at top), A1B (in the middle) and A2 (at bottom) for the years 2020-2029 and 2090-2099. The three scenarios range from the most favourable (B1) to one with continued considerable use of fossil fuels (A2) and accordingly reflect, above all, the uncertainty regarding future emissions of greenhouse gases.

If great efforts to stem climate change are not made quickly or if the sensitivity of the climate system is greater than has generally been supposed to be the case, and if air pollution in the form of smoke and dust is reduced, the concentration of greenhouses gases may increase sharply and correspond to 750 ppmv CO_2 or even more, which could entail a global temperature rise of up to perhaps 5°C. Uncertainty of these conclusions is evident in Figure 7.2 where the two alternative developments (550 and 750 ppmv, respective roughly correspond to scenarios B1 and A2. The uncertainty in the projection of future temperature increases in these two cases is also evident from the range of results from the series of calculations of different global climate models which are also shown in the left hand panels of Figure 7.2.[2]

IPCC further asserts that a warmer climate will increase the rate of the now ongoing deglaciation of all the mountain glaciers on Earth. Most will have disappeared within several decades to half a century. It is, however. still difficult to determine to what extent the increasing melting from the lower parts of the Greenland ice now and in the future will be compensated by the accumulation of snow over the Greenland high plateau.

Hansen (2007) warns, however, for both faster and greater change than that predicted by IPCC but there is still a lot of uncertainty despite increased research efforts. IPCC's conclusions are the starting point for the following.

- According to IPCC it is improbable that the Antarctic inland ice will be appreciably influenced by the reinforced greenhouse effect for many centuries to come. There is no appreciable deglaciation taking place over the land-based ice but a rather close equilibrium has been established over thousands of years between precipitation in the form of snow over the continent and a slow movement of the ice masses towards the surrounding sea where calving occurs. The inertia of the system is great and it is thought that only very special circumstances can change this.

Also with regard to this question Hansen (2007) asserts that there are considerable risks that the water level may rise by a meter before the next century and bases this on the risk that parts of the ice in the western Antarctic, which in large part rest on the sea bottom, would be able to float away from the archipelago which presently holds them in place. Their water content above the present sea level has about the same volume as the Greenland ice.

Thus it is probable that the carbon dioxide concentration in the atmosphere will at least double during this century. This will also have important consequences for the terrestrial and marine ecosystems. A warmer climate will increase the productivity of the terrestrial ecosystems on condition that access to water and nutrients is sufficient, but only to a certain limit. Increased drought in, above all, sub-tropical areas is perhaps the most important threat. A more

[2] It should be pointed out that the figures above refer to the changes since the beginning of the 1900's, while Figure 7.1 shows the changes from IPCC's reference period 1980-1999 when the increase of the global average temperature of 0.4-0.5°C had already taken place.

extensive adaptation to new climatic conditions also takes time. That change is occurring has been concluded above all by the climb of the timber line in certain mountainous areas. On a time-scale of 50–100 years however more destructive change can become significant with a risk also of a return flow (net) of carbon dioxide from the terrestrial systems to the atmosphere (Cramer, 2001). Changes in the extension of the climate zones may also occur rather quickly if more prolonged drought hits the areas which are productive today. There is also a risk that a warmer climate will increase the rate of decomposition of the organic content of the soil which likewise means a return flow of carbon dioxide to the atmosphere.

The flow of carbon dioxide into the ocean slowly reduces the pH of the sea water. The pre-industrial value was ca. 8.20. Up to the present it has decreased by around 1.10 units and a continued development such as that outlined above will probably lead to a further decrease of ca. 0.20 units. This can have important consequences for many marine ecosystems, which constitutes a further threat to be added to the depletion of the ocean's living resources which is taking place *inter alia* due to over-fishing. Organisms forming calcite shells and coral reefs are already considerably affected, the latter because of an increase in the temperature in coastal and shallow areas. A reduction in the productivity of the ocean will also reduce the transport to greater depths of the carbon dioxide which is absorbed from the atmosphere at sea level. A decreased number of dead plankton will descend to the bottom which in turn may diminish the role of the ocean as a sink for the increasing quantities of carbon dioxide in the atmosphere.

7.3 What can happen during the thousand years beyond 2100?

As already pointed out the insolation which reaches the Earth, like its distribution over the globe, changes only slowly and will, to a large extent, remain unchanged over the next thousand years. This means that the warm period which now prevails probably would have continued a while still, even if a reinforced greenhouse effect had not come into the future picture. But how long it will endure remains the central question.

The conclusions of the discussion in the foregoing section are, however, that there is an important risk that the amount of carbon dioxide in the atmosphere will increase rather than decrease even after man's emissions to the atmosphere have been sharply reduced. A stabilisation or a decrease in the concentration of greenhouse gases in the atmosphere beyond 2100 will quite likely be the long-term goal of the Climate Convention even if formal decisions in this respect have not been taken. However, the change to a warmer climate which is taking place during the present century will probably, nevertheless, not disappear within the course of a century or two but may possibly continue during a considerable part of the present millennium, particularly if the amount of carbon dioxide in the air at the beginning of the next century reaches 750 ppmv or more, but there is considerable uncertainty in such a judgement.

IPCC has systematically analysed alternative climate scenarios beyond 2100 on the basis of the increasing number of published studies which are now available. The starting point should reasonably be the character of the carbon cycle during the 1800's and the centuries before that.[3] A natural redistribution between the atmosphere, the terrestrial systems and the ocean of the at least ca. 1,000 billion tons (gigaton, Gt) carbon (i.e. ca. 4,000 Gt CO_2) which probably will have been added to the atmosphere by 2100 will occur slowly - the time-scale is 100-500 years - and it is the relatively large stores of carbon in the terrestrial systems, above all the soil, and deep ocean which are the end stations for man's emissions. The warmer and, in wet areas, generally more humid climate, which is being established during the present century will therefore probably remain for centuries to come. A better specification than this is hardly possible at present.

The climate change during this millennium can, however, be of decisive importance for the question of the Greenland ice to be or not to be over the coming thousand years. A less controlled development of the climate with a global warming of 3–4° C, or perhaps even more, would probably lead to a considerable deglaciation and a gradual decrease in the elevation of the high plateau of the

[3] During the centuries before man's massive use of fossil fuels there were quantities of carbon in the atmosphere, the terrestrial ecosystems and the oceans:

The atmosphere, as carbon dioxide	ca. 600 Gt C
The terrestrial systems vegetation	ca. 500 Gt C
Soils down to ½-1 m	ca. 2,000 Gt C
The oceans, as CO_2, H_2CO_3, HCO_3^{-1}, CO_3^{-2}	
surface layers, 1-100 m	ca. 1,000 Gt C
Thermocline, 100 m-1,000m	ca. 10,000 Gt C
Deep sea, 1,000 m-bottom	ca. 28,000 Gt C

Greenland ice which is now ca. 3,000 m above sea level. It is also possible that “the point of no return” will be reached followed by a more rapid deglaciation before the close of the millennium.

The risk for a catastrophic collapse of the ice in the western Antarctic would, of course, also increase. Beyond these very uncertain judgements the warming of the ocean will, in any case, continue over a large part of this millennium with, initially, a considerable increase in the level of the ocean, i.e. at about the rate which, according to IPCC, can be expected during the present century, i.e. 20-60 cm.

A summarised *subjective* review of this situation leads to the conclusion that the sea level may rise by 1–2(5) m during the present millennium where (5 m) indicates a faster deglaciation of the Greenland ice and possibly increased deglaciation in western Antarctica. The situation would, by the end of the millennium in that case, resemble what prevailed during the warm period Eem ca. 120,000 years ago when the water level was probably ca. 6 m higher than today. But these conclusions are uncertain and are understood only as an uncertain possibility in IPCC’s conclusions.

7.4 Climate change over the coming ca. 100,000 years

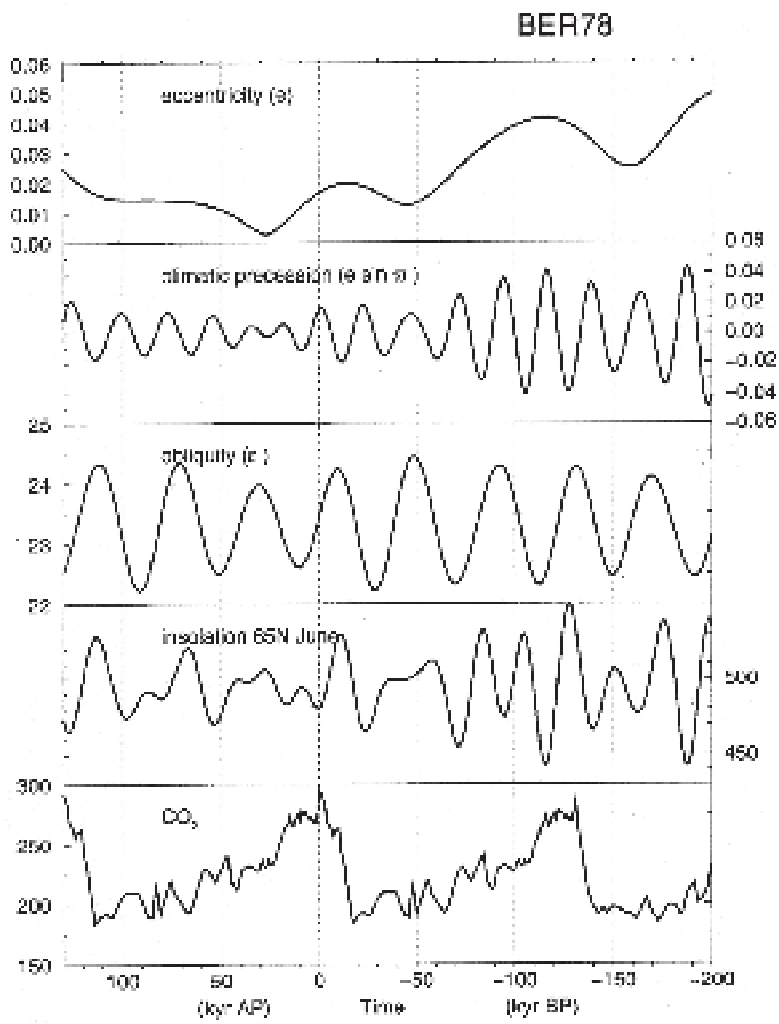
Will a warmer climate remain for thousands of years and will a new ice-age be postponed until the future or will a colder climate nevertheless return within a relatively short period. This is obviously the key question which must be further explored.

It is not technically possible to use the complex climate models which were set up to study climate variations during the 1900’s and later centuries to calculate changes over the coming hundreds of thousands of years. Instead, considerably simpler models have been developed and calibrated with the help of observed climate change over the last century and calculations with complex climate models during the time that the now ongoing climate change has taken place.

Berger and his colleagues already calculated early-on the incoming insolation variations and distribution over the Earth during the entire Quaternary period on the basis of astronomical factors and later extended these calculations to also encompass hundreds of thousands of years into the future. The research group has subsequently developed a relatively simple climate model and studied future scenarios which arise out of the different assumptions about the interplay between the factors which principally determine the Earth's future climate. Apart from changes in astronomical conditions and variations in carbon dioxide, the climate model includes important processes such as:

- The connection between the concentration of water vapour in the atmosphere and the temperature
- The link between the temperature of the atmosphere and the Earth's albedo, i.e. its ability to reflect insolation back into space
- The interplay between climate and vegetation, for example the change of snow-covered tundra to taiga
- The changes in the thickness of inland ice dependent on increased precipitation
- Isostatic changes in the topography of the land surface dependent on the thickness of the inland ice

Figure 7.3 Variations of the eccentricity, precision and tilting of the Earth's axis towards the ecliptic and the intensity of insolation at summer solstice at 65° N latitude over the last 200,000 years and up until the next 130,000 years. Furthermore carbon dioxide concentrations over the last 200,000 years are shown as are the corresponding variations from today and 130,000 years into the future (see the text below).



Source: Berger et. al., 2003.

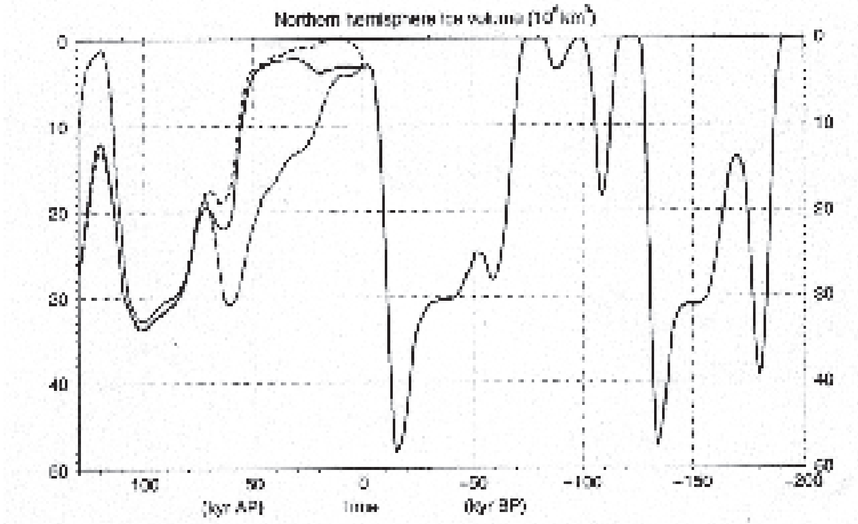
The three uppermost graphs in Figure 7.3 show the time changes of the three astronomical parameters which decide insolation variations in time and space on the Earth (eccentricity, precision and tilting of the Earth's axis towards the ecliptic). The precision determines variations of the point in time when the Earth is near or far from the sun in its elliptical orbit around the sun, which influences the conditions of the incoming insolation as a function of season and latitude. Consequently the fourth graph shows insolation variations (in Wm^{-2}) on latitude 65° N in June over the last 200,000 years and up until the next 130,000 years. These variations are of prime interest so as to be able to judge the change in climate the high latitude of the Northern hemispere a longer perspective.

The latest warm period was obviously initiated by significantly increasing insolation over that northern area 15,000 to 10,000 years ago and a very significant increase in insolation can also be seen ca. 130,000 years ago when the warm period Eem began. On the other hand, the coming ca. 50,000 years will be characterised by relatively small variations in the astronomical factors which determine the incoming insolation. Already this gives a hint that the variations between the ice-ages and the warm periods would perhaps be different over many tens of thousands of years in the future compared to conditions during earlier warm periods.

We know that the concentration of carbon dioxide varied markedly during the latest ice-age (Petit et al., 1999). Measurement of its concentration in the small air bubbles which were successively captured when the Antarctic inland ice was formed, shows a successively declining concentration from ca. 280 ppmv during the Eem warm period to only ca. 210 ppmv up until ca. 15,000 years ago (see Figure 7.3, the fifth graph). We know that these variations are in some way related to the gradual cooling, but do not know the more precise causes.

Berger and his colleagues have tried to simulate climate change over the last 200,000 years with regard to the above-mentioned factors. To test the sensitivity of the climate system they made two assumptions on the insolation variations and carbon dioxide concentrations during this time (Berger et al., 1998). The conclusions of these calculations are that even if the concentration of carbon dioxide is considered to have been constant, ca. 230 ppmv (i.e. the average concentration which prevailed during that time) the model shows clear variations in temperature between ice-ages and warm periods. The variations in carbon dioxide are insufficient to primarily generate the observed climate change but they reinforce the astronomical driving forces.

Figure 7.4 The volume of ice in the northern hemisphere calculated with the help of the LLN 2-D model as influenced by the variation of insolation and carbon dioxide over the last 200,000 years to the next 130,000 years



Source: Berger, et al., 2003.

The solid curve (which shows ca. 3x10^6 km^3 over the coming ca. 50,000 years) is calculated on the assumption that the amount of carbon dioxide has varied as in Figure 7.3. The dotted curve (which shows increasing volumes of ice already within a few thousand years) is derived from the assumption that the quantity of carbon dioxide in the atmosphere was 210 ppmv while the dashed curve shows the results if the amount of carbon dioxide is assumed to be ca. 750 ppmv. The volume of ice increases downwards in the figure.

In its later work the group made similar alternative experiments to reach greater clarity about alternative future changes (Berger et al., 2003), cf. Figure 7.4. Concentration of carbon dioxide over the next 130,000 years has been assumed to be (1) constant at 210 ppmv, (2) varied as for the last 130,000 years, and (3) constant at 750 ppmv. In the first-mentioned case a return to ice-age conditions will begin in the rather near future, in the second case the present warm period will continue for the next ca. 50,000 years.

The latter assumption implies that a strong reinforcement of greenhouse effects over one or several thousand years would lead to the Greenland ice melting in the relatively near future but nevertheless not hinder a transition to ice-age conditions in ca. 50,000 years.

7.5 Conclusions

To sum up, these calculations show that an insolation level at summer solstice of ca. 480 Wm^{-2}, and with relatively small variations, will be predominant over northern Scandinavia during the next ca. 50,000 years. The climatic system is, under these circumstances, relatively sensitive to changes of the greenhouse effect which man has already instigated and may further increase in the future. However, it is also important to underline that the astronomical factors which determine the character of the climate vary on a time-scale from some tens of thousands of years to ca. 100,000 years (or more) while natural changes of the concentration of carbon dioxide in the atmosphere (for example adaptation to man's emissions of greenhouse gases) occurs on time-scales from hundreds to some thousands of years. Our knowledge of the adaptation of the carbon cycle to the situation which man has created through his emissions up until now and may continue to create over the next centuries, is insufficient to be able to determine if, for example, the Greenland ice will disappear or not, or if the western Antarctic inland ice possibly will float to the ocean. However, there is a somewhat increased risk that this may happen if the carbon dioxide concentration in the atmosphere more than doubles during the next few hundred years and that the increase will last for perhaps thousands of years.

The changes which are outlined above will be noticed in Scandinavia in different ways. The rising water level in the ocean and the slowly sinking land masses around the southern part of the Baltic Sea and the continental land area further south will enable an increased exchange of water between the North Sea and the Baltic Sea and possibly also increased salinity in the Baltic Sea. It may also imply a slowly rising water level around southern Götaland (the most southerly part of Sweden) over, at least, thousands of years. Land upheaval in the Gulf of Bothnia should still be able to keep in step with the rise in the water levels of the ocean over thousands of years to come, as long as ice break-up and melting of the ice in the western Antarctic and in Greenland does not accelerate.

A relatively warm climate, compared to the conditions of today, is probably linked to increased precipitation, perhaps above all over northern Scandinavia with accompanying changes in the hydrology and vegetation in these areas. It is, however, nearly impossible to analyse the effect of such changes in relation to a future population in these areas (and also other adjacent areas), when we can hardly imagine how a future society will develop over thousands of years to come.

What may happen in the long-term during a warm period which will last for perhaps 50,000 years, is necessarily mostly speculation.

7.6 References

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8 Concluding reflections

When we plan our daily calendar we must know not only what we will do but also where we will be and, above all, when we will be there. We have developed tools to measure time and a formal scale to decide it. We use one second as a basic unit to measure time. Exactly what is a second? From 1900 until 1968 we defined a second as 1/31 556 925 947th part of year 1900. Now a second is defined as “the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the atom caesium 133”. This unit of time is measured by an atomic clock, the so-called caesium clock.[1] We count sixty seconds in a minute, sixty minutes in an hour, twenty-four hours in a day, which is about the time it takes for the Earth to make one revolution around its axis.

We speak of time in generations and if, on average, we regard twenty years as a generation, we can say that known history started two hundred to four hundred generations ago. On the other hand, geological time began with the origin of the Earth around 4,600 million years ago. It may be added that many cultures regard geological time in about the same way as historical time.

The time dimension plays a major role in all the discussions concerning final disposal of nuclear waste. The radioactivity in the spent nuclear fuel decreases with time but at very different speeds for different elements and for their different isotopes. When it comes to the handling of high-level waste and spent nuclear fuel, the goal is, of course, to establish a repository which meets high demands for safety for hundreds of thousands of years to come. Only then will the radioactivity have decayed to the same level as the surrounding environment. This is a time perspective which humans have difficulty in understanding.

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[1] Quoted from the National Encyclopaedia (1994), volume 13, **p. 572.**

However, from a human perspective, the work which has been done and which will be done in the future to find and concretely accomplish some form of final disposal of spent nuclear fuel also covers a long period, in the order of a century or more. To view the length of such a period in perspective, it may be compared to the lifespan of large investments in society's infrastructure (roads and railways, electricity and telecommunication networks). The design and implementation of such investments also often require long periods which are of the same order of magnitude. An important difference however, is that it is difficult to indicate an exact end-point for work with investments since they more often are subject to continuous renovation and improvements. On the other hand, "final disposal of spent nuclear fuel" may be regarded as an industrial project with a given end-point. This stage may be identified as the day when all the material which is intended to be finally deposited has been brought to the repository and this has been sealed in a way which has been planned in advance.

At the same time, the future hundred thousand years period that is indicated above for the decay of the radioactivity in the spent nuclear fuel must be seen in perspective of what occurred in nature during the corresponding period in the past. We should then recall that, as already mentioned, the geological history of the Earth stretches back 4,600 million years and that the latest geological time period, the Quaternary, is thought to have started 2-3 million years ago.

Which governing processes in nature have existed up until now and what developments can we predict for the future? Can we at all predict how a final repository for spent nuclear fuel will develop up until the point when the radioactive radiation has decayed to its natural level?

How has society changed over the last 50 years, i.e. from the time when nuclear power began to be developed for peaceful purposes? And to what extent are we able to predict the developments leading to a society that will decide on and carry out final disposal of spent nuclear fuel?

The Swedish National Council for Nuclear Waste (KASAM) has the following composition:

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The Swedish National Council for Nuclear Waste – KASAM – is an independent scientific committee within the Ministry of the Environment. Its mandate is to advise the Government in matters relating to nuclear waste and the decommissioning of nuclear installations. KASAM's members are independent experts within different areas of importance for the disposal of radioactive waste, not only in technology and science but also in such areas as ethics, the humanities and the social sciences.

KASAM's activities include describing the state of knowledge in the nuclear waste field every third year in a so-called state-of-the-art report. The 2007 report on the state-of-the-art in the nuclear waste field is the ninth in this series. This year the report consists of a main report entitled *"Nuclear Waste, State-of-the-Art Report 2007 – responsibility of those now living, freedom of future generations"* (SOU 2007:38), plus four in-depth reports. These are:

- *Final disposal of spent nuclear fuel – regulatory system and roles of different actors during the decision process* (KASAM Report 2007:1e),
- *Safety assessment of final disposal of nuclear waste – role, development and challenge* (KASAM Report 2007:2e),
- *Time for final disposal of nuclear waste – society, technology and nature* (KASAM Report 2007:3e) and
- *Risk perspective on final disposal of nuclear waste – individual, society and communication* (KASAM Report 2007:4e).

The present report on the time for final disposal of nuclear waste constitutes one of the in-depth reports. The aim is to provide the reader with an understanding of the different time perspectives which are relevant for a final repository for nuclear waste whether the focus is on society, technology or nature.

All reports are available at www.karnavfallsradet.se.

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