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Handling of future human actions in the safety assessment SR-Can

Svensk Kärnbränslehantering AB

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Preface

This document describes the handling of future human actions relevant in an analysis of long-term safety of a KBS-3 repository. It supports the safety assessment SR-Can, which is a preparatory step for a safety assessment that will support the licence application for a final repository in Sweden.

The report is authored by Lena Morén, SKB. The report mainly builds on translations from Swedish of the report SKB R-98-54, that supported an earlier safety assessment of a KBS-3 repository. The Swedish report was edited by Lena Morén and co-authors were Tom Ritchey and Maria Stenström, Swedish Defence Research Agency. Tom Ritchey has reviewed the translatated and editited version given in this report.

The report has been reviewed by Mike Thorne, Mike Thorne and Associates, UK.

Stockholm, October 2006

Allan Hedin
Project leader SR-Can

Contents

1 Introduction

1.1 Structure and purpose of the report

This report documents the future human actions (FHA) considered in the long-term safety analysis of a KBS-3 repository. The report is one of the supporting documents to the safety assessment SR-Can (see further the **Main report**).

The purpose of this report is to provide an account of:

- General considerations concerning FHA.
- The methodology applied in SR-Can to assess FHA.
- The aspects of FHA that need to be considered in the evaluation of their impact on a deep geological repository.
- The selection of representative scenarios for illustrative consequence analysis.

As further described in the **Main report** and the **FEP report** (Features events and processes report) the content of this report has been audited by comparison with FEP databases compiled in other assessment projects.

1.2 Previous work

In their review of SKB's (Svensk Kärnbränslehantering AB, the Swedish Nuclear Fuel and Waste Management Co) programme for research, development and demonstration – RD&D 95 – SKI (the Swedish Nuclear Power Inspectorate) pointed out that SKB:

"… must develop their own strategy for how issues relating to human intrusion should be handled in future safety assessments."

SKI further stated that the work performed within OECD/NEA (Organisation for Economic Co-operation and Development/Nuclear Energy Agency) /OECD/NEA 1995a/ was an adequate basis for the development a strategy to handle FHA. Based on this, SKB developed a strategy to handle FHA for the safety assessment SR 97 /Morén et al. 1998, SKB 1999/.

Future human actions that can affect the safety of a repository involve questions concerning the evolution of society and human behaviour. These are questions that cannot be answered by conventional scientific methods. For example, it is not possible to predict knowledge that does not exist today, and knowledge is judged to be a key factor in this context. By necessity the strategy must be based on present-day knowledge, obtained from people alive and active today. To get a broad view of the multifaceted question of FHA an ambition was to, in line with the NEA working group recomendations /OECD/NEA 1995a/, involve people active within a broad spectrum of relevant fields in the development of a strategy. For this purpose the development was based on the results from workshops to which people with varying knowledge and backgrounds were invited. In total three workshops were held:

1. Skebo December 1997, with the purpose of supporting the choice of scenarios involving FHA to be included in safety assessments and providing a basis for the development of a strategy to handle FHA.
2. IVA March 1998, to make a list of human actions that can affect the safety of the final repository, based on current technical knowledge and a description of that repository, and describe and justify the actions in technical terms.

3. Frösunda May 1998, to construct framework scenarios (framework conditions) that describe feasible societal contexts for FHA that can affect the radiological safety of a deep geological repository.

The results from the workshop at Skebo together with the recommendations of the NEA working group /OECD/NEA 1995a/ formed the basis for the development of the strategy presented in SR 97 /SKB 1999/. At the two latter workshops, the strategy was further developed and partly carried out. The results from the workshops were reported in Swedish /Morén et al. 1998/. In the safety assessment SR 97 /SKB 1999/, the developed strategy and the results from the technical and societal analysis carried out at IVA and Frösunda were used to select FHA scenarios for which consequences were analysed.

1.3 Documentation of participating experts

The experts participating at the workshops mentioned in the previous section and their fields of knowledge are documented in Appendix A. The results of the workshops were reported in Swedish by Lena Morén (SKB), Tom Ritchey and Maria Stenström (former FOA, Swedish Defence Research Agency now FOI, Swedish Defence Research Institute) /Morén et al. 1998/. The experts from FOI contributed as did the other participants to the workshops to the development of the strategy. In addition to this, they contributed the methodology applied in the analysis of societal conditions. They both organized and reported the workshop on societal aspects at Frösunda. Tom Ritchey has also reviewed the summary and translation of this work as presented in Chapter 5 of this report.

2 General considerations

The general considerations concerning FHA set out below are mainly based on the report of the NEA working group on future human actions at radioactive waste disposal sites /OECD/NEA 1995a/ and ICRP Publication 81 /ICRP 1998/.

2.1 Waste management principles

There are in theory two different options for managing hazardous waste:

- convert to it to a harmless form; or
- dispose it.

Spent nuclear fuel can be regarded as a resource or a waste. In the former case, the valuable substances, i.e. specific heavy nuclei, are separated/reprocessed from the spent fuel and used as fuel in different kinds of fission nuclear reactors. Alternative systems including one or several re-circulations of the spent fuel, and one or more separation processes and reactor types are possible /SKB 2000/. They all have in common reduction in the content of long-lived heavy radionuclides and increase in the content of short- and long-lived fission products compared with the case of direct disposal of the spent fuel. Thus, the spent fuel is not converted to a harmless material, but to another hazardous form that still requires disposal. In Sweden only a small amount of spent fuel has been reprocessed and direct disposal of the spent nuclear fuel is planned.

Waste disposal strategies can be divided into two conceptual approaches /ICRP 1998/:

- Dilute and disperse.
- Concentrate and retain.

The latter principle applies to the planned final disposal of spent nuclear fuel in a KBS-3 repository. The spent nuclear fuel and the hazardous radioactive substances it contains will be collected and kept isolated from man and environment, currently in an interim storage facility and later in a KBS-3 deep geological repository. The intent is to totally isolate the spent fuel from man and the environment for as long a time as possible. The potential exposure to large quantities of the radiotoxic material is an inescapable consequence of the deposition of the spent nuclear fuel in one final repository. Consequently both natural processes potentially prejudicing isolation and human intrusion have to be considered in the development and safety assessment of such a disposal system /ICRP 1998/.

2.2 Responsibilities between generations

There is an international consensus /e.g. IAEA 1995, 1997, OECD/NEA 1995b/ also clearly stated in Swedish law /SFS 1984:3/ that the society that receive the benefits, or more specifically the nuclear power producers that receive the profits, of the electric power production and generate the radioactive waste should bear the responsibility for developing a safe disposal system. In doing so, the freedom of action and safety of future generations have to be taken into account, as far as reasonable possible. However, current society cannot be required to protect future societies from their own intentional and planned activities, if they are aware of their consequences. This is valid irrespective of the intent of the planned actions, i.e. whether they are carried out for benevolent or malicious reasons. Based on this consideration, it is concluded that only inadvertent human actions need to be considered in the design and safety assessments of repositories for radioactive waste.

The NEA working group on assessment of FHA at radioactive waste disposal sites define inadvertent actions as:

"Those in which either the repository or its barrier system are accidentally penetrated or their performance impaired, because the repository location is unknown, its purpose is forgotten or the consequences of the actions are unknown."

In line with this reasoning only inadvertent future human actions with the potential to affect the repository barrier functions are considered in the design and safety assessment of the KBS-3 repository. Also in line with this reasoning and the ICRP recommendations, the following countermeasures to reduce the probability of inadvertent intrusion and potential for exposure to the spent fuel have been applied in the siting and design of the KBS-3 repository:

- The repository is located at a site not containing exploitable natural resources;
- The repository depth is greater than the depth of interest for water supply and more generally occurring sub-surface facilities;
- The repository will be sealed so as to make subsequent entry difficult;
- Measures will be taken to preserve institutional control and information concerning the repository for as long as possible.

The long-term safety of a final repository for spent nuclear fuel or radioactive waste is required to be maintained by a system of passive barriers and must not depend on surveillance, maintenance or any other active measures taken by future generations to sustain the safety. However both with the purpose to reduce the probability of inadvertent FHA affecting the repository and to provide required safeguards there will be some kind of institutional control of the repository after it has been closed. Further actions will be taken to preserve information concerning the repository, its content and barriers.

2.3 Future human actions considered in long-term safety assessments

In Section 2.2, the responsibilities of current and future generations are discussed. Retrievability is an issue often debated in the context of the responsibilities of current and future generations. As the retrieval of the spent nuclear fuel from a sealed repository would be an intentional action, the potential dose associated with the retrieval from the sealed repository is a risk the generation deciding to retrieve the spent fuel must consider. The intention is to seal the KBS-3 repository when all spent nuclear fuel from the Swedish nuclear power program has been deposited and retrievability after closure of the repository is not included in the KBS-3 concept. The KBS-3 repository facility will, however, adopt a design strategy and include provision of equipment that would make retrieval of deposited canisters during the construction and operation phases possible if major faults or errors that could threaten post-closure safety are discovered. Consequently doses related to retrieval are an issue for the assessment of the operational safety of the repository, and such retrieval is not included in the long-term safety assessment.

After closure of the repository, people should be able to freely utilize the site according to their needs. Descriptions of ongoing local human activities and land use are included in the biosphere part of the site descriptions and also accounted for in defining the initial state of the biosphere in the long-term safety assessment. Future possible land use is considered in the descriptions of ecosystems that may occur at the site taking into account their possible long term development, e.g. as a result of climate change. The sites are used by humans today and most likely will be so also in the future. Known and possible future human actions and land uses must not adversely impact the safety functions of the repository. In the long-term safety assessment, they are included in the biosphere description and identification of critical groups, see further the **Biosphere at Laxemar**, **Biosphere at Forsmark** and **Biosphere process reports**.

There are also ongoing global human activities that may affect the repository, e.g. pollution of air and water and the emission of greenhouse gases. In the time perspective of the long-term safety assessment, major climate changes are expected. Changes related to the climate, e.g. shoreline displacement, and the development of permafrost and ice sheets, are the most important naturally occurring external factors affecting the repository in a time perspective from tens of thousands to hundred of thousands of years. Climate-related changes are included as part of the reference evolution and the main scenario in the safety assessment. The emission of greenhouse gases may impact the climate and thus indirectly the repository, and this matter is considered as a variant of the main scenario. The emission of greenhouse gases is, therefore, not included among FHA considered in this report, however pollution, e.g. acidification of air and water, which may have a direct impact on the repository, is considered.

The kind of FHA that are the main issue in Chapter 4 of this report and that were also the main concern in the report from the OECD/NEA working group /OECD/NEA 1995a/ and of the ICRP /ICRP 1998/ are local, post-closure actions with potential impact on the final repository. It is also this kind of actions that SSI mentions in their background and recommendations /SSI 1998/ and general guidelines /SSI 2005/ to their regulations. As discussed in Section 2.2 only inadvertent actions, i.e. actions carried out without knowledge of the repository's location, its purpose or the consequences of the actions, are considered. The actions that can be expected to have the most serious consequences are actions that impair or totally disrupt barrier functions or barriers.

3 Strategy to handle FHA

The SKB strategy or method to handle FHA in long-term safety assessment was developed for the post-closure safety assessment SR 97. It was outlined based on the conclusions of the NEA working group on assessment of future human actions at radioactive waste disposal sites /OECD/NEA 1995a/ and the results from the workshop at Skebo in December 1997.

Since the strategy was suggested, SSI's "Regulations on the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel and Nuclear Waste" /SSI 1998/ and SKI's "Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste" /SKI 2002/ have been issued. SKI's general recommendations concerning the application of the regulations and SSI's background and comments to their regulations, as well as the general guidelines to SSI's regulations provided in 2005 /SSI 2005/ include some recommendations as to the handling of FHA in the safety assessment. These documents, as well as ICRP Publication 81 /ICRP 1998/ have been taken into account in this report. Further SKI's and SSI's review comments /SKI 2001/ as well as the viewpoints of international reviewers of SR 97 /SKI 2000/ have been considered. Another document that was reviewed and considered in this slightly updated version of the SR 97 strategy is "Elements of a regulatory strategy for the consideration of future human actions in safety assessments" /Wilmot et al. 1999/. In the application of the strategy, developments in technology, knowledge and description of the KBS-3 repository and its functions since SR 97 have been taken into account.

3.1 The SKB strategy or methodology to handle FHA

The SKB strategy or methodology to handle FHA consists of the following steps.

A. Technical analysis:
Identify human actions that may impact the safety functions of the repository and describe and justify the actions in technical terms.

B. Analysis of societal factors:
Identify framework scenarios (framework conditions) that describe feasible societal contexts for future human actions that can affect the radiological safety of a deep repository.

C. Choice of representative scenarios:
The results of the technical and societal analyses are put together and one or several illustrative cases of future human activities are chosen.

D. Scenario description and consequence analysis of the chosen cases.

Recommendations and viewpoints from the NEA working group on FHA /OECD/NEA 1995a/, the workshop at Skebo /Morén et al. 1998/ and SSI's /SSI 1998, 2005/ and SKI's /SKI 2002/ regulations of importance for the development and application of the strategy are summarized below.

3.1.1 The NEA working group

The NEA working group stated that the analysis of FHA can only be illustrative and never complete. By applying a systematic approach to scenario development, a set of scenarios "*describing what can be reasonable contemplated – rather than what will be*" can be identified. Probabilities assigned to scenarios based on FHA are bound to be subjective. It is, however, important to as completely as possible investigate the range of conceivable FHA. The working group recommended that experts from a range of scientific and social disciplines should be involved in the selection and analysis of FHA. The identified FHA were then required to be considered in the safety assessment, as well as in repository siting and design, and the development of countermeasures.

The FHA scenarios can be "*viewed as representations of potential realities based on sets of assumptions*" and the consequence analysis "*must therefore be considered as potential impacts based on these sets of assumptions*". To avoid speculations about the future, the scenarios and assumptions in the consequence analysis can "*be based on the premise that the practises of future societies correspond to current practises at the repository location and similar locations elsewhere*". The working group also discussed different possible countermeasures to avoid inadvertent intrusion into the repository or disruption of barrier functions. They concluded that active institutional control is the most effective countermeasure, but that it cannot be relied on in the time perspective of long-term safety assessments.

3.1.2 The workshop at Skebo

The purposes of the workshop in Skebo were to:

- support the selection and formulation of scenarios concerning human actions for SR 97,
- contribute to the development of a strategy to handle FHA in performance assessments.

In this section only the comments and conclusions relevant to the development of a strategy are quoted.

An appropriate strategy to handle FHA must provide a systematic and comprehensive approach to selection, justification and descrition of a set of scenarios based on human actions to be included in a safety assessment. It is desirable to avoid speculations and, as far as possible, base the scenarios on documented historical and sociological knowledge. However, since the future of humans and society are unknown, the question is whether a systematic review of current knowledge can support the choice of the human actions on which the scenarios are based. Can current humanistic and sociological knowledge be utilized to select more likely actions, e.g. to judge whether drilling is more likely than construction of a rock cavern, or will the sketching of scenarios in which man plays a central role never be more than pure speculation?

The initial discussions of the workshop concerned factors that can influence future human actions on the repository site, and what might trigger an action that affects repository safety. Factors of a widely differing nature from human anxiety to technology were judged to be important. Examples of discussed factors are; values, mood, society, knowledge, intent, motive, geographic conditions and technology. The importance of different factors and their rates of change were discussed. The workshop concluded that describing the background of a scenario based on human actions is primarily a humanistic, sociological problem, whereas the detailed description of the action is primarily a technical problem.

For the technical aspects, the repository functions – isolation and retardation – and the ways that they are achieved can be used to identify actions that can affect the safety of the repository. Thus the design and function of the repository serve as a basis for the identifying and describing a set of cases selected for their potential impact on the safety of the repository.

A review of humanistic and sociological aspects can contribute background descriptions comprising plausible societal contexts and motives as to why people in these situations would disrupt the repository. By proceeding methodically, relevant factors or parameters can be identified, varied and combined to explore different plausible outcomes. In this way, it should be possible to define the most important factors and identify dangerous combinations of them. The results can be used in the safety assessment when explaining and assessing the cases selected for their potential impact on the repository. They can also be used to support the development of countermeasures against FHA that may disrupt the repository.

The discussions and conclusions from the workshop explain the division of the analysis of FHA into a technical and societal part, yielding results that can be combined in the selection of representative cases to be included in the safety assessment.

3.1.3 SSI's and SKI's regulations and recomendations

In their regulations, SSI states that "*the consequences of intrusion into a repository shall be reported*". In the background and recommendations to the regulations, intrusion is defined as "*inadvertent human actions that impair the protective capability of the repository".* The essential is not to account for the actions resulting in the intrusion, but to illustrate the safety functions of the repository after the intrusion.

In the general guidelines to the regulations /SSI 2005/ it is said that:

"*A number of scenarios for inadvertent human impact on the repository should be presented. The scenarios should include a case of direct intrusion in connection with drilling in the repository and some examples of other activities that indirectly lead to a deterioration in the protective capability of the repository ...*"

"*The selection of intrusion scenarios should be based on present living habits and technical prerequisites and take into consideration the repository's properties.*"

Regarding the reporting of consequences it is clarified that *"... the disturbance of the repository's protective capability should be illustrated by calculations of the doses for individuals in the most exposed group, and reported separately apart from the risk analysis for the undisturbed repository ...*". The consequences for the individuals performing the intrusion need not be assessed.

In the general recommendations to their regulations SKI /SKI 2002/ says that the impact of human activities shall be included among external conditions that affect repository performance. Future human activities and their impact on the repository barriers should be included in the category "*less probable scenarios*". This category of scenarios "*should be prepared for the evaluation of scenario uncertainty*". Scenario uncertainty is classified as "*uncertainty with respect to external and internal conditions in terms of type, degree and time sequence*".

SSI's and SKI's regulations mainly affect the application of the strategy and the account of FHA and their consequences in the safety assessment.

4 Technical analysis

4.1 Scope and methodology

4.1.1 Scope

The technical analysis comprises identification of human actions that may impact the safety functions of the repository, and descriptions of, and justification for, the actions in technical terms. The results of the technical analysis presented in the following sections of this chapter are mainly based on the conclusions from the workshop at IVA in March 1998 /Morén et al. 1998/. A group of engineers with good knowledge in the fields of geotechnics, geology, geohydrology, chemistry and systems analysis attended the workshop. The results from the workshop have been updated based on consultation with technical experts within SKB and the development of technology, knowledge and the description of the KBS-3 repository and its functions since SR 97. The identified actions have also been audited and compared with the external FEPs in the NEA FEP[1] database. External FEPs are those operating outside and generating boundary conditions for, the FEPs governing radionuclide, release and transport, and radiological impact.

4.1.2 Methodology

The technical analysis was in line with the NEA working group's and SSI's recommendations, in that it was based on current technical practises. To identify actions with potential impacts on repository safety, the functions of the barriers and the variables defined as function indicators were used. The functions and function indicators are described in the **Main report** and illustrated in Figure 4-1.

To facilitate the analysis, to avoid duplication of actions with similar purpose and impact, and to generate as complete a list of FHA as possible, the actions were distinguished into thermal (T), hydrological (H), mechanical (M) and chemical (C). A human action is defined as belonging to a certain category if:

- a process belonging to the category is affected by the action,
- the purpose of the action is to utilize a resource that can be said to belong to the category,
- the purpose of the action is to perform a task that can be said to belong to the category.

To determine if a process belonging to the category was affected, the set of physical variables that define the state of the canister, buffer, backfill and geosphere and the classification of processes into thermal, mechanical, hydrological or chemical in the **Fuel and canister-, Buffer and backfill-** and **Geosphere process reports** were used. It should be mentioned that most of the identified human actions would impact variables and processes belonging to more than one of the categories T, H, M or C. The actions judged to have the greatest impact on the repository always include some kind of mechanical impact, e.g. drilling or excavation.

The purpose of the technical analysis is to make a list of human actions that can affect the repository system, and describe and provide motivation for the actions in technical terms. Beyond this, some general technical aspects relating to the human actions have been identified.

[1] The NEA FEP (Features Events and Processes) database consist of a headline structure to which features, events and processes considered in different safety assessments have been linked.

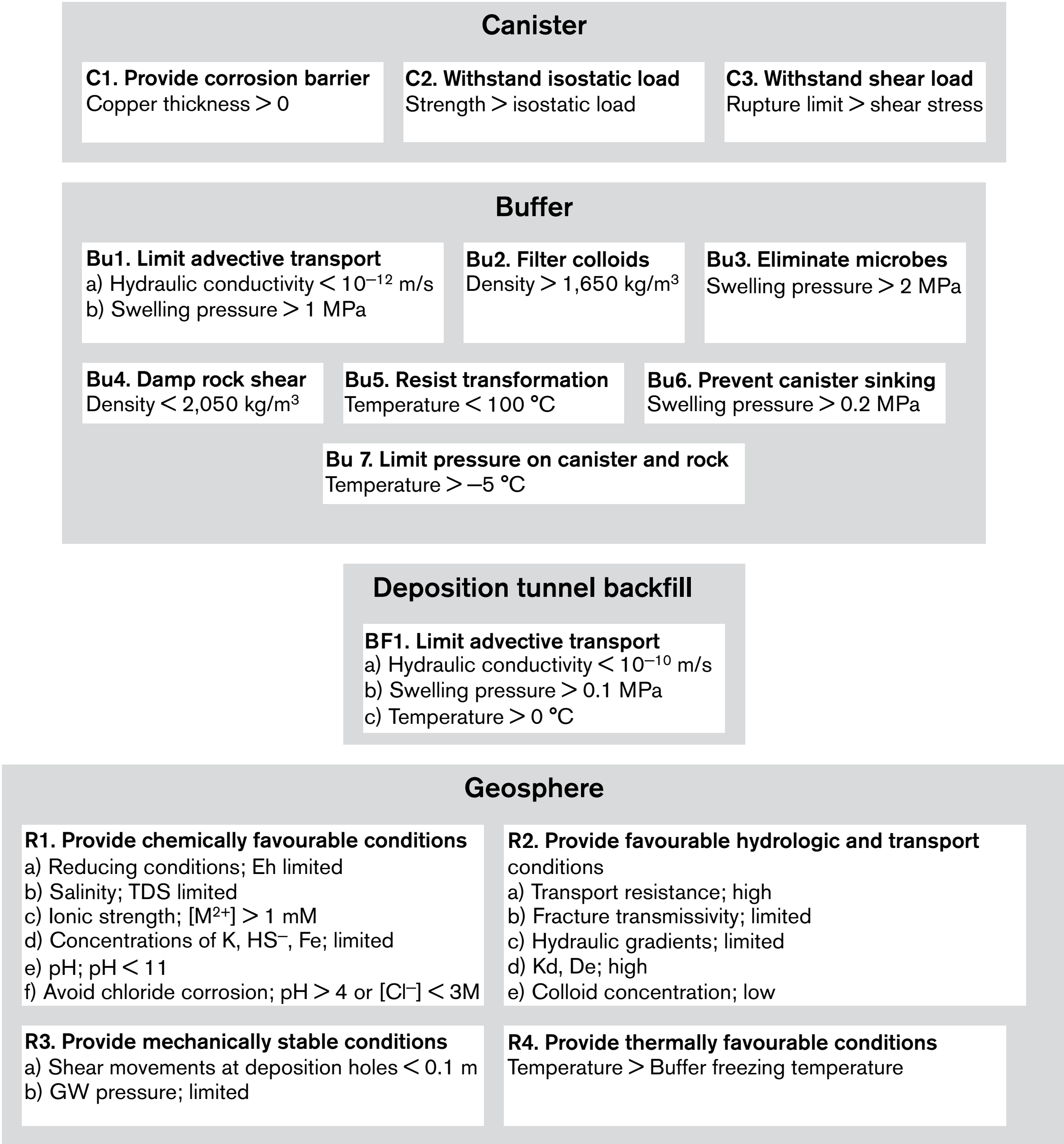

Figure 4-1. *The safety functions and related function indicators of the different barriers of the repository.*

4.2 General aspects

4.2.1 Siting and design considerations

Human actions were taken into account in site selection. The repository will be built in a commonly occurring type of rock lacking special minerals that could be regarded as a natural resource. Areas with potential for extraction or storage of heat have been avoided. If the rock itself is considered to be a natural resource, the fact that the rock type is commonly occurring means that this resource is readily available in large parts of the country. It is difficult to find reasons why rock should be extracted from great depths.

Human actions have also been considered in the design of the repository e.g. in the choice of repository depth and the design of backfill and sealing of tunnels and shafts. Drilling or excavating down to repository depth requires machinery and – barring substantial technical advances – a great effort and investment. The repository is designed to maintain its safety functions given extensive changes to the environment at the surface. Human activities at the surface affecting the surface environment must thus entail great changes in order to affect the repository's safety functions of isolation or retardation.

4.2.2 Economics and technology

Extensive changes in the conditions on the surface above a repository, including drilling or construction in the rock, will always entail a great effort. Someone must be willing to pay for this effort. The payment can be achieved because the action yields a profit, e.g. it consists of a resource utilization of some kind. It can also be paid by someone, e.g. the power industry, the state or a private company who for some purpose decides to change the surface environment, drill or construct some kind of sub-surface facility. Whether the action is worth the investment in time, money and materials, depends on both the magnitude of the investment and the willingness of the sponsor of the action to make that investment. Only more or less realistic expectations to find large quantities of valuable material can warrant investigation and prospecting projects.

Technological development may make various actions cheaper and easier to carry out. The judgement as to what is a resource is linked to the value of the resource and the costs of utilizing it. Technological development can be driven by the high value of a resource. Thus, economics and technology are linked.

Conditions in society change relatively rapidly. Facilities created by man which are used for some special purpose and involve some type of continuous operation are often dependent on prevailing technical and societal conditions. It can be assumed that such facilities will be operated for periods of tens to hundreds of years at the most. When the facility is no longer in operation it may be abandoned without measures being taken to restore the site to the condition that it was in before the facility was built.

4.3 Future human actions that may impact the repository

Table 4-1 presents human actions that can affect the repository divided into THMC categories. In the following sections, the different categories and the actions defined as belonging to them are explained, described and commented upon.

Table 4-1. Human actions that can affect a deep repository, divided into THMC categories.

Category	Action
Thermal impact	T1: Build heat store
	T2: Build heat pump system
	T3: Extract geothermal energy (geothermics)
	T4: Build plant that generates heating/cooling on the surface above the repository
Hydrological impact	H1: Construct well
	H2: Build dam
	H3: Change the course or extent of surface water bodies (streams, lakes, sea) and their connections with other surface water bodies
	H4: Build hydropower system
	H5: Build drainage system
	H6: Build infiltration system
	H7: Build irrigation system
	H8: Change conditions for groundwater recharge by changes in land use
Mechanical impact	M1: Drill in the rock
	M2: Build rock cavern, tunnel, shaft, etc
	M3: Construct quarry
	M4: Construct landfill
	M5: Bomb or blast on the surface above the repository
	M6: Subsurface bomb or blast
Chemical impact	C1: Store waste in the rock
	C2: Construct sanitary landfill
	C3: Acidify or in other way polute air, water, soil and/or bedrock
	C4: Sterilize soil
	C5: Cause accident resulting in chemical contamination

4.4 Actions with thermal impact and purpose

The interior of the earth is hot. Disregarding seasonal temperature variations in the near-surface layers, the temperature increases with depth. At a certain depth – which varies between the different parts of the country – the temperature is independent of the season. Below this depth, the temperature in the bedrock is greater than on the surface for most of the year. Crystalline rock has a relatively high heat capacity (about half the specific heat capacity of water on a volumetric basis). Heat capacity is greater in basic rock than in acidic rock, but the difference is not very great (about 10–20%).

In other words, the rock contains thermal energy (heat). This heat can be extracted, and the rock is also a good potential heat storage medium. The heat capacity of the rock can be of importance in locating heat stores. At temperatures above the boiling point, the heat can be converted to other forms of energy. Such high temperatures occur at very great depths in the type of rock where a deep repository is planned. At lower temperatures, the heat can be utilized for space heating.

Since the temperature in the rock is not very high (12–15°C at a depth of 500 metres), additional measures are often required, for example a heat pump, to make use of its heat content. To determine whether a heating system is efficient, it is necessary to take all parts of the system into account. In home heating, for example, factors that influence heating efficiency are building insulation, ventilation and radiators.

The deep repository will cause an increase in the temperature of the rock. This improves its potential for both extraction and storage of heat. In crystalline rock the temperature gradient is about 1.6°C per 100 metres. The presence of the repository will result in an increased gradient. If the repository is built at a depth of 500 metres, the gradient will be about 6°C/100 metres at 1,000 years after deposition of the spent fuel and about 2.5°C/100 metres after 10,000 years.

This heat anomaly can easily be detected with simple instruments, for example an ordinary thermometer during well drilling. If the increased temperature is detected or known, the repository site may be chosen over others for extraction and storage of heat.

4.4.1 Heat storage

Premises

Thanks to its heat capacity and uniform temperature, the rock can be used to store thermal energy. The uniform temperature conditions can also be utilized for the location of facilities that require a low or stable temperature. The heat in a heat store is supplied and stored in hot water. The water may have been heated by the sun or be waste heat from some industrial enterprise. Large stores – with large volume in relation to area – at great depths have the greatest potential. Such an installation requires extensive excavation. With current technology, the cost of building a heat store is so great, and the price of energy so low, that such stores are seldom economical.

Technology

The hot water is stored in rock caverns, which may be filled with boulders, or in boreholes. A borehole storage system consists of many boreholes into which the hot water is pumped. The rock around the borehole may be fractured by blasting. The technology exists today, and pilot systems have been built.

Rock caverns for heat storage are built relatively near the surface, at a depth of a few tens of metres. The temperature increase with increasing depth is not crucial for the system's efficiency. However, the temperature gradient is lower at greater depths, resulting in lower losses, so the choice of depth of the store is an optimization question.

The number and depth of the boreholes in a borehole storage system depend on how much heat is to be stored. A large number of boreholes drilled to a depth of several hundred metres may be required for large communities.

Impact on the repository and its functions

A heat storage facility will affect thermal, hydrological, mechanical and thermal state variables and processes in the geosphere. The extent and nature of the changes depends on how the store is designed and constructed. If the construction and investigations for the facility comprise drilling of deep boreholes, the isolation may fail if a canister is penetrated, see further Section 4.6.1. The heat storage facility may affect the geosphere's capability to provide favourable hydraulic and transport conditions. This may indirectly affect the capability of the geosphere to provide chemically favourable conditions. Water pumped down into the store may be oxygenated or contain unwanted pollutants.

4.4.2 Heat pump system

Premises

Only ground-source heat pump systems are addressed here. The energy can be extracted either by circulating water or another heat transfer fluid through boreholes in the rock (closed-loop system), or by pumping up the groundwater (open-loop system). In the former case, a temperature gradient develops towards the borehole. This gradient varies between the winter and summer seasons. If groundwater is utilized directly as the heat source, the groundwater flow rate must be great enough to cover the need. With today's conditions, heating of a single-family home requires about 25 times more water than the household's other water consumption requirements. Today, the most common solution is to circulate a heat transfer fluid through the borehole. Heat pump systems can be combined with heat storage.

Technology

The technology is available today and many systems are in operation. Systems for small buildings with boreholes in which a heat transfer fluid circulates in a closed loop are common. One 100-200 metres deep borehole can supply a single-family home with its energy needs, but larger houses may require two such boreholes. In densely built-up areas, systems with several deeper holes supporting several households are possible, although this is not very common today. The depth of the boreholes is both related to the energy need and the capacity of the drilling equipment, see further Section 4.6.1. Development of heat-pump technology and drilling methods as well as the construction of the buildings and their heating systems (radiators etc) influences the design and economics of the systems. There is an ongoing development of equipment for percussion drilling down to 1,000 metres depth (G Nilsson, 2006, SKB personal communication). Drilling to depths down to 500 metres or more for the extraction of heat is performed today and may become more common in the near future.

Impact on the repository and its functions

A ground-source heat pump system affects thermal, and to some extent, hydrological processes and state variables in the geosphere. If water is pumped up, hydrological processes will be directly affected. The hydrological impact of small systems of the type described above is considered to be limited. In general, the impact of such systems on repository functions is judged to be of no importance. Large systems with several deeper boreholes will affect the temperature in the bedrock and may impact the geosphere's capability to provide favourable hydraulic and transport conditions.

4.4.3 Geothermal energy – geothermics

Premises

By "geothermal energy" is meant here energy that can be used directly, without storage or concentration in a heat pump. Sites with potential for extraction of geothermal energy have been avoided in the siting process. With current technology, such systems require temperatures of at least 150–200°C. At the potential repository sites, the depth where such high temperatures are found is about 10,000 metres. The heat can either be extracted by pumping up hot groundwater or by pumping water from the surface through natural and/or blast-induced fractures in the hot rock. Since the groundwater flux at great depth in crystalline rock is limited, this latter type is most likely.

Technology

The technology exists in theory today, but no systems to the great depths that would be required at a site similar to the candidate sites exist today. In a system for extraction of geothermal heat, at least two boreholes are drilled and connected *via* a fracture system. On one side water is pumped down and on the other side up. The water is heated as it passes through the fracture system. Systems of this type exist in areas where the temperature increases rapidly with the depth. No systems drilled to the great depths that would be required at sites similar to the candidate sites exist today. There are only a few boreholes in the world with depths of 8-10,000 metres or more. They are drilled for exploratory purposes. If geothermal energy were to be utilized at sites similar to the candidate sites for a deep repository, drilling techniques would have to be developed substantially.

Impact on the repository and its functions

If a system of the type described above should nevertheless be built, it would probably not have any significant impact on the repository, since the operational zone would be located far below the repository. The boreholes would locally affect the function indicators fracture frequency and transmissivity, but the impact of the geosphere's capability to provide favourable hydrologic and transport conditions is considered to be insignificant. If a borehole were to pass through the repository, there is a possibility that a canister would be penetrated, see Section 4.6.1.

4.4.4 Plant on the surface above the repository

Premises

Temperature gradients are a driving force for groundwater flow, although usually less important than pressure gradients. If the temperature change itself is to affect the safety of the repository, temperatures below freezing or above boiling at repository depth are required. It is difficult to imagine a surface plant that would generate heating/cooling that could affect the repository, and there are no examples of such plants today.

4.5 Actions with hydraulic impact and purpose

Sweden is located for the most part in the temperate climate zone. Annual precipitation is generally between 400 and 600 mm and averaged over the year exceeds the evaporation. Due to the precipitation rate, other climatic conditions and the low permeability of the bedrock, the groundwater table largely follows the topography. The landscape contains many lakes and streams. Past glaciations have left eskers that contain a great deal of water. The permeability of the rock seems to decline with depth. Down to about 200 metres depth, the permeability is generally greater than at greater depths. Close to the surface, the groundwater flow can be several orders of magnitude greater than at repository depth. Salt water is always present at great depth. Fresh water is found closer to the surface. The depth to salt water is dependent on local conditions and the hydrogeological and hydrogeochemical history of the site. Except in some coastal areas and on small islands, potable water is available near the surface in the bedrock in most parts of the country.

The KBS-3 repository will be built in a rock formation that is free of major water-conducting fracture zones. The water flux in the rock volume in which the repository is built should be low. There is, therefore, little chance that water will be withdrawn from this particular rock volume.

4.5.1 Well

Premises

Only rock wells are discussed. Wells where the water is used as drinking water or for irrigation are drilled through water-conducting zones. Their depth is normally between 50 and 100 metres, but some wells reach down to 130–150 metres. Deeper wells are very uncommon. The reason is that it is expensive to drill and that the probability of hitting potable water in sufficient quantity declines with depth. An exception is if a major deep water-conducting zone has been mapped and is drilled into. These cases involve large-scale water withdrawals and not wells for private use. In the light of hydrological conditions in Sweden, it is difficult to see any reason why drinking water should be taken from great depths. One reason for taking water from great depth may be that it is warmer than the water near the surface, as is discussed in Section 4.4.

Technology

The technology exists, and there are many rock wells in the country.

Impact on the repository and its functions

The well is included as part of the biosphere in the safety assessment. Withdrawal of water from a well affects the groundwater flow conditions in the rock. The impact on the function of the repository of commonly occurring wells would be limited.

4.5.2 Dam

Premises

Dams are built to create a water reservoir, if topography and other ground conditions are suitable. The reservoir may be used for fish farming, drinking water, irrigation, hydropower, etc. Dams may also be built for recreational or aesthetic purposes.

Technology

The art of building dams is old and the technology well known.

Impact on the repository and its functions

A dam locally affects hydraulic gradients. If a dam is built, areas that have previously been groundwater recharge areas can become discharge areas, and vice versa. The conditions for groundwater infiltration are changed. However, the impact on the rock's capacity to provide favourable hydrological and transport conditions are deemed to be insignificant, as the effects are not expected to propagate to respository depths.

4.5.3 Changes in surface water bodies

Premises

Surface water bodies can be altered by changes in land use associated with e.g. agriculture or forestry or any kind of construction. The direction and flow of streams can be altered; canals can be dug to link streams, lakes and the sea. Sea bays can be diked, wetlands can be drained, etc. Surface water bodies on a site can always be changed by man if this is deemed desirable.

Technology

People have been utilizing, building and altering surface water bodies for centuries. The technology exists and is employed.

Impact on the repository and its functions

The impact on the repository is similar to that for dam construction, see 4.5.2.

4.5.4 Hydropower plant

Flowing water with an elevation difference (head) is needed to build a hydropower plant. A hydropower plant includes a dam and often also tunnels and rock caverns.

For a description of the technology, and potential impacts on the repository and its function, see Sections 4.5.2 and 4.6.2.

4.5.5 Systems for drainage or infiltration

Construction in the rock requires drainage, so that the rock cavern will not fill with water. Near-surface layers may be drained to make the areas suitable for some special purpose. Drainage changes the ground conditions.

In gas storage systems, water seals consisting of channels injected with pressurized water surrounding the rock cavern can prevent gas from leaking out. In heat storage systems, hot water may be infiltrated. In urban areas where large surface areas are used for buildings or covered with a relatively impermeable coating, water can be infiltrated to prevent lowering of the groundwater table and thereby altered ground conditions, see Section 4.5.7.

For a description of the technology and the impact on the repository, see Sections 4.4.1, 4.5.3 and 4.6.2.

4.5.6 Irrigation system

An irrigation system requires a source of water. The source may be a well, reservoir or surface water body. Surface water can be utilized directly or by construction of canals or ditches. Irrigation affects the conditions for groundwater infiltration. See also Sections 4.5.1, 4.5.2 and 4.5.3.

4.5.7 Changes in land use

Changes in land use affect the conditions for groundwater recharge. The magnitude of the impact depends on how land use is changed. For example, if land surface areas are built on and/or covered with some relatively impermeable coating, groundwater recharge will be reduced. This affects the ground conditions and can lead to subsidence damage to buildings as well as landslides. The way in which the land is utilized by people is an important part of the biosphere description.

4.6 Actions with mechanical impact and purpose

Crystalline rocks are hard and brittle materials with high compressive strength and low tensile strength. They have a density of about 2.7 t/m^3. Rock excavation involves methods that cause such great stresses that the rock falls apart and can be removed.

4.6.1 Drill in the rock

Premises

To investigate the properties of the bedrock at great depth, one or more boreholes are often drilled. Prior to most major rock excavation projects, several holes are drilled to investigate the bedrock. Deep boreholes may also be drilled for research purposes. Besides investigation of the bedrock, boreholes may be drilled to sink a well, build a system for heat extraction or storage, or to infiltrate water or some other fluid into the rock.

The repository comprises a heterogeneity in the rock. The spent fuel emits heat. The deviation from conditions in the surrounding rock caused by the repository can be detected from the surface. If information on the repository has been partially or completely lost, the deviation may arouse curiosity and the site may be investigated by drilling.

Technology

The art of drilling deep holes in rock has existed for over 100 years. Today the following drilling methods are employed:

- Core drilling.
- Percussion drilling.
- Down-the-hole hammer drilling.

In core drilling, a drill core is retrieved. The drill consists of a rotating metal cylinder, and water is used to remove drill cuttings and to cool the drill. Core drilling is used in investigation and prospecting. In percussion or hammer drilling, the rock is pulverized by a device that strikes, twists and crushes. The pulverized rock material is removed by water. Percussion drilling is used to drill wells and to drill boreholes to extract or store heat. Today’s standard percussion drill rigs are capable of drilling to a maximum depth of 200–250 metres, but there is an ongoing development of equipment for percussion drilling down to 1,000 metres depth (G Nilsson, 2006, SKB personal communication). In down-the-hole hammer drilling, the hammer device is placed down in the borehole. Down-the-hole hammer drilling is used to drill very deep holes.

In drilling with any method, it is likely that if tunnels, buffer or canister are hit the heterogeneity they comprise will be discovered. A core drill could penetrate the buffer and canister and radioactive materials could be brought to the surface. If a backfilled tunnel is hit when core drilling, the water cooling the drill and bringing the cuttings to the surface will be glutted with fine-grained material. The usual procedure is then to try to flush the fine-grained material away. If this does not succeed, which is plausible if trying to drill through the backfill, the borehole will be grouted and the drilling continued. In percussion drilling, the canister would constitute an obstacle, since copper is a ductile material that cannot be crushed in the same way as the hard, brittle rock. It is likely that the drilling would be stopped if a canister was hit when percussion drilling.

Impact on the repository and its functions

If holes are drilled to great depths within the repository area, there is a small probability of penetrating a canister and thereby breaching the isolation of the waste. If a canister is penetrated, spent nuclear fuel will be brought to the surface and people will be exposed to the radionuclide content. If the isolation of the waste is breached, the borehole will be a transport pathway for radionuclides. The rock's capacity to provide favourable hydrological and transport conditions will be degraded. If water is pumped out of the borehole the transport conditions are further affected. If it does not penetrate a canister, the impact on the repository will depend on how deep the borehole is and what it is used for. A borehole that passes close to the repository with a purpose that affects thermal, hydrological or chemical state variables or processes can affect the goesphere's capability to provide favourable hydrological, transport and chemical conditions.

4.6.2 Rock caverns, tunnels, shafts, etc

Premises

One reason for building tunnels and shafts in the rock is for mining purposes, i.e. to extract minerals in the rock. Rock caverns may also be built for the purpose of storing something. The rock is chosen as a storage medium because it is suitable due to prevailing conditions (temperature, pressure, chemical environment, etc). The purpose is to protect the stored material from outside influences, or the surrounding environment from the stored material. The reason for placing a facility sub-surface can also be that there is not enough room on the surface or the land is considered very valuable for some reason. In densely built-up areas, tunnels are built for vehicle traffic, power and telephone lines and sewers. The rock can also be utilized for various fortifications and shelters. Rock caverns can also be used for weapons testing.

Since building in rock is expensive, rock caverns are generally located as near the surface as possible, depending on their purpose. In many cases, rock cover of a few tens of metres is enough. In some cases, conditions are better at greater depth. An example is a repository for hazardous waste, which takes advantage of the hydrological, mechanical and chemical conditions deep down in the bedrock. Another example involves taking advantage of the increased temperature at greater depth; see Section 4.4. Another reason for utilising greater depths is the pressure conditions. Rock caverns at depths of 500-1,000 metres can be used to store compressed air for gas turbines. Rock caverns with water seals for gas storage can be built at the same depth. A rock cavern can also be built for the purpose of obtaining a water head in order to generate electricity. For such a plant to be profitable, periodically fluctuating electricity prices are required. The plant generates electricity when prices are high, and during low-price periods the water is pumped up again.

Technology

The technology is known. Examples of rock caverns at great depths are found in the mining industry. Blasting is normally used for rock excavation. In some cases drilling is used.

Impact on the repository and its functions

A rock cavern near the repository would affect the geosphere's capability to provide favourable hydrological and transport conditions. If the rock cavern is kept dry, water flux and conditions for transport of substances with the groundwater will be affected. Abandoned rock caverns, tunnels, shafts and boreholes are potential transport pathways for undesirable substances to and from the repository. A rock cavern may also affect the geosphere's capability to provide chemically favourable conditions. For example, during operation of a sub-surface facility close to the repository, salinity can increase at repository depth. The temperature in the bedrock will also be affected, but it is deemed unlikely that it will fall below 0°C or rise above 100°C. The closer to the repository the rock cavern is located, the more the repository is affected.

4.6.3 Quarry

Premises

The bedrock at the potential repository sites consists of commonly occurring crystalline rocks. Similar conditions exist on about 50% of Sweden's surface. If someone wanted to mine the rock as a resource, a quarry is the most likely alternative. Since stone is heavy, good conditions for transport between the quarry and the place of use are an important siting factor. Drainage needs can also be a factor in selection of a quarry site. For example, the quarry can be constructed on a height. Since it is easier to mine near the surface and crystalline rock is plentiful, it is likely that the depth of the quarry would be limited to a few tens of metres.

A formation where the rock has unusually high quality – for example high strength, beautiful colour and texture, or is easy to split – gives the raw material a higher value. In such cases, it is likely that a quarry may be dug deeper, perhaps down to hundred metres. Such areas have been avoided in the repository siting process.

Technology

The technology exists; blasting with charges adjusted to the desired size of the rock blocks will be utilized.

Impact on the repository and its functions

The geosphere's capability to provide favourable hydrological and transport conditions may be affected. Since rock surfaces would exposed, conditions for groundwater infiltration would be altered. The groundwater composition, at least near the surface would also be altered. If the chemical environment were altered this would mainly be a result of the altered hydrological and transport conditions.

4.6.4 Landfill

Premises

Undesirable waste products are often deposited on confined sites (landfills). Stone and soil material can also be dumped in landfills. Landfills are often located on land deemed to be of less value, but favourably situated for transport purposes.

Technology

The waste product can be deposited directly on the site. In some cases, the land is prepared by e.g. drainage or creation of an impermeable layer.

Impact on the repository

The landfill comprises a mechanical load. The load is judged to be negligible in relation to natural variations in the stresses in the rock, for example during a glaciation. A landfill affects the conditions for groundwater infiltration. Groundwater composition is affected, at least locally and near the surface. It is, however, uncertain if the chemically favourable environment at repository depth would be altered. This depends on the composition of the dumped material and measures in the form of drainage, impermeable layer and the like.

4.6.5 Bombing or blasting on the surface above the repository

Blasting on the surface is often done in conjunction with various kinds of construction. It may be a question of blasting away a bit of rock that is considered to be in the way, or excavating basements or road cuts. Measures of this kind are considered not to affect the safety of the repository.

Bombs may detonate on the surface of a repository in wartime or if the site is used as a weapons testing site. A bomb that detonates near the ground surface creates a crater, and the rock fractures locally. Normally the safety of the repository would not be affected, as the changes would only penetrate to a few metres or, at most, tens of metres. A bomb that could threaten the repository would have to have a very powerful pressure wave. If such a bomb were to detonate on the surface, the consequences would be disastrous regardless of whether they lead to a release of radionuclides from the repository or not. Testing of such large bombs in peacetime is unthinkable. If bombs of this size were dropped in wartime, the consequences would probably be such that any radionuclide releases from a deep repository can be regarded as negligible.

4.7 Actions with chemical impact and purpose

The bedrock is a very effective filter for most substances and compounds. However, a strong complexing agent can change the situation by increasing the mobility of the metal ions it forms complexes with. If there are leaky canisters, such substances affect the capacity of the rock to retain radionuclides. Colloidal particles may also have relatively high mobility and a high capacity to absorb radionuclides. Surfactants can help to stabilize colloidal suspensions and thereby adversely affect the rock's capacity to retain radionuclides.

4.7.1 Disposal of waste in the bedrock

Premises

The waste has been collected and the rock has been deemed to be a suitable place to dispose of it. If this method is chosen to dispose of some type of waste, the choice has probably been carefully considered. It is also likely that the rock where the waste is to be disposed of will have been investigated. If the investigated site is located close to the deep repository, it is likely that the repository will be discovered and recognized as a waste repository.

Siting, design, construction and operation of repositories for radioactive waste have contributed to the development of this method for disposing of hazardous waste. Both technology and methods for evaluating the safety of waste repositories have been developed. Furthermore, operating facilities can influence people's attitude to this type of waste disposal.

Technology

The waste can be placed in rock caverns or injected into the bedrock. If the waste is placed in rock caverns, the repository can be provided with various kinds of barriers. The waste is probably in such form that it is judged to be stable in the environment offered by the rock. If it is injected, the waste must be in liquid form. If drilling technology becomes much cheaper and more accessible than today, it is conceivable that waste will be disposed of in this manner.

Facilities for geological disposal of radioactive operational waste are in operation. Repositories for spent nuclear fuel are planned in a number of countries. There are also plans to dispose of mercury in rock caverns. Technology to inject waste exists and is said to have been employed in the former Soviet Union. Boreholes are drilled to a suitable depth. The waste is injected directly into the bedrock or into an area fractured by blasting or hydrofracturing.

Impact on the repository and its functions

If boreholes are drilled for investigation of the rock, a canister could be penetrated, see Section 4.6.1. If waste is injected into the rock, depending on the properties of the injected substance, the geosphere's capability to provide chemically favourable conditions may be affected. The capability of the rock to provide favourable hydrological and transport conditions may be affected especially during construction and operation of a waste repository. Injected substances or substances that escaped from a closed waste repository could also affect the rock's capacity to retain radionuclides.

4.7.2 Contamination with chemical substances from the surface

The bedrock can be contaminated with substances via landfills, due to air and soil pollution or due to accidents. If soil layers are sterilized or removed from the site, substances that would otherwise have been transformed or accumulated there can get down into the rock. Contamination with chemical substances from the surface must be very extensive in order to affect the safety of the repository. In this case, the contamination in itself entails such serious consequences that any further contribution to impacts on human health and the environment by radionuclides is likely to be negligible in comparison.

5 Societal analysis

5.1 Scope and methodology

5.1.1 Scope

The societal analysis comprises the identification of framework scenarios (framework conditions) that describe feasible societal contexts for future human actions that could affect the radiological safety of a deep repository. The framework scenarios should be seen as background descriptions, in other words they should only serve as plausible societal contexts for different possible human actions with safety-related and/or radiological consequences. The intent is to investigate and identify plausible motives for why people in different socio-technical future situations would disrupt the repository. Only unintentional motives are investigated and the time perspective is limited to the next 50-500 years.

The societal analysis and identification of framework scenarios presented in the following sections of this chapter is mainly based on the results from the workshop at Frösunda 1998 /Morén et al. 1998/. The analysis was carried out by Tom Ritchey and Maria Stenström (both from former FOA now FOI) who suggested the application of the methodology, organized the workshop where the methodology was applied and reported the results. The work of Ritchey and Stenström was reported in Swedish and is included as a part of /Morén et al. 1998/. The text in this chapter is mainly a summary of a translation of their text. However, Section 5.1.2 contains text from an article written by /Ritchey 1997/ and Section 5.2 also refers to results from the workshop at Skebo, 1998. The societal aspects discussed have also been audited and compared with the external FEPs in the NEA FEP database.

5.1.2 Methodology

Methodological problems

We cannot see into man's future. The evolution of human society is strongly dependent on the development of scientific knowledge, ideas and principles. We cannot, on the basis of present knowledge, predict what new scientific knowledge will emerge. There is no formal, scientific method for predicting knowledge which we do not yet know about /Popper 1957 in Ritchey 1997/. In other words, the long-term outlook for fundamental scientific discoveries and the development of new scientific principles is, *in principle*, unpredictable. Since fundamental scientific knowledge is closely linked to technological innovation and technoproductive applications, we cannot say with any certainty what is *possible or impossible* when it comes to man's ability to affect or develop nature, society and himself /Ritchey 1977/.

The best we can do is, based on current knowledge, to identify some important variables (dimensions or factors) which we can then vary and combine in different ways to explore possible outcomes. In doing so, we must be aware of our basic ignorance of future scientific discoveries. If man was able to control the biosphere, the climate and biological evolution or change what we today regard as the basic physical laws of nature, then we would be living under completely different conditions. Based on this reasoning, it is not meaningful to speculate on possible, probable or plausible societal contexts for future human actions in very long-term perspectives. The time perspective is thus limited to 50–500 years ahead in time; even in this time span the future of man and society is completely unpredictable.

Methodology

Uncertainties can be divided into *determinate* or *specified* and *indeterminate* or *unspecified*. Great uncertainty can be related to a determinate uncertainty, but the outcome space for the uncertainty is well defined and complete. An example of determinate uncertainty is "the population of Sweden 2500". If population is unambiguously defined, a whole number from zero and upwards can be given. An example of indeterminate uncertainty is "fundamental scientific discoveries made during the coming 500 years". In this case, the total outcome space is not known, i.e. cannot be described completely or in terms of predetermined measures or categories. When dealing with the future of man and society the uncertainties are indeterminate.

Even if the uncertainties are unquantifiable scientific methods can be applied. Scientific knowledge develops through cycles of analysis and synthesis: every synthesis is built upon the results of a proceeding analysis, and every analysis requires a subsequent synthesis in order to verify and correct its results /Ritchey 1991/. However, analysis and synthesis – as basic scientific methods – say nothing about a problem having to be quantifiable. Complex societal problems can – on a sound scientific basis – be analysed into any number of non-quantifiable variables and a range of conditions for each of these variables. Similarly, sets of non-quantifiable conditions can be synthesised into well-defined relationships.

For the sought framework scenarios some important variables (dimensions or factors) can be identified. A set of inter-related variables (dimensions), each with a range of (discrete) conditions organized in a matrix is a way to express a *morphological field,* an example of such a matrix is shown in Figure 5-2. Configurations of conditions involving one condition from each variable represent a state of the field, and form the basis for scenario descriptions, see Figure 5-3 for an example. In *morphological field analysis*, morphological fields are used for structuring, analysing and evaluating multi-dimensional problem complexes that do not lend themselves to quantification. For application of morphological field analysis, FOA has developed the software CASPER (Computer Aided Scenario and Problem Evaluation Routine). CASPER supports the following process:

- to *define* and *structure* the variables (dimensions) of the problem and organize them into a matrix,
- to *analyse* the possible range of conditions that these variables (dimensions) can express,
- to *evaluate* consistent sets of relationships within these complexes and to *synthesise* plausible, internally consistent outcomes or "scenarios" that they can generate,
- to *document* and *display* the outcomes in a way that provides a good overview of the total problem complexity and allows for provision of an audit trail.

It is emphasised that CASPER is a process tool, i.e. the process that the working group goes through in using the tool is the most important result of the work. In the results, the process involved in arriving at the conclusions is documented together with the structured overview of the total problem-field and the conclusions drawn. At the workshop at Frösunda, morphological field analysis was applied and CASPER was used.

5.2 Considered societal aspects

The societal aspects of importance for the occurrence of FHA that may impact the repository can be expressed via a set of variables or factors. Such variables or factors and the conditions they express were discussed both at the workshops in Skebo and Frösunda and are summarized in the following sections.

5.2.1 Variables or factors discussed at Skebo

At Skebo the following variables or factors were identified as important for FHA:

- values – threats and risks e.g. physical or economical, democratic values, symbolic values e.g. for or against nuclear power and resource utilization e.g. virgin status of the land,
- mood – emotional state of individuals and groups or in society as a whole e.g. confidence/anxiety, security/insecurity, and influence/powerlessness,
- society – or societal aspects such as nation-building, form of government, public authorities and their role, and the existence of various groupings,
- knowledge – both knowledge of the repository and the general state of knowledge in society and also the distribution of knowledge, i.e. whether it is highly polarized or evenly distributed,
- intent – benevolent or malicious, self- or public interest,
- motive – e.g. curiosity, exploration, utilization of the waste as a resource, construction of rock facility or changes in land and water use,
- geographic conditions – physiographic conditions, climate, population and infrastructure,
- technology – technology that is utilized to carry out the action.

Examples of values that were discussed were threats people may associate with a repository for spent fuel, e.g. the risk of being exposed to radioactivity and threats to property values. Other discussed aspects of values were the repository's symbolic value for or against nuclear power, resource utilization and the virgin status of the land and democratic values. Values were considered important for actions at the repository site, and also for the design of both the repository and countermeasures against human intrusion. Threats to values people regard as important could also be a triggering factor for sabotage. Mood referred to the emotional frame of mind of individuals and groups or in society as a whole. The feelings or moods described can vary with regard to confidence/anxiety, security/insecurity, and influence/powerlessness. Feelings may in turn reflect different conditions in society such as stability/instability, homogeneity/heterogeneity, power relationships, ideology and state of knowledge.

Knowledge was identified as a key issue in scenarios related to FHA. It is, for example, linked directly to intent. The general knowledge level is also important. Will future generations be able to interpret available information on the repository? If the detailed information on the waste and/or the function of the repository has been partially lost and the repository is rediscovered, will people understand what they have found? Will they be able to restore those functions of the repository that may have been impaired? The changes in the general knowledge level and knowledge of the deep repository and how these are related to each other and the motive and intent for FHA at the repository were discussed; the results are illustrated in Figure 5-1. This illustration can be compared with the analysis and scenarios presented in Section 5.3 and the conclusions from the societal analysis in Section 5.4.

5.2.2 Variables in the morphological field

Variables

Of the variables discussed at Skebo values and mood were not explicitly identified at the workshop at Frösunda, but can be considered to be included in the variables "Purpose of disruption", "Knowledge" and "Form of society", see further Section 5.2.2.

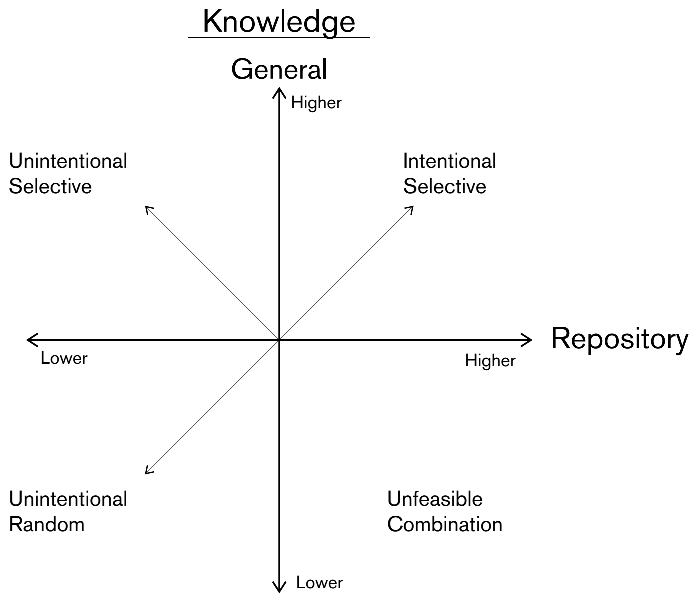

Figure 5-1. *Changes in knowledge and its relation to intent and motive of FHA at the repository site. The origin represents the current situation and the arrows indicate how the likely intent and motive of FHA would develop given the illustrated development of knowlwdge.*

The working group at Frösunda in a first phase of their work identified and discussed the following ten variables:

- *Climatic conditions* around the repository.
- *Human settlements* and the demographic pattern at or near the repository location.
- *General scientific and knowledge level* in society compared with today.
- Technological level of society's physical *infrastructure* compared with today.
- Capacity of society's *transportation system*.
- Capacity of society's *information system*.
- *Knowledge* in society *of the repository*'s existence.
- Existence and effectiveness of *society's supervisory mechanisms* and regulatory framework.
- Legitimacy of *government* and degree of governability.
- *Purpose* of disrupting the repository.

Regarding purpose only unintentional motives are investigated. For methodological reasons, however, it is important to first identify and define a broader set of framework variables that includes both intentional and unintentional motives and that may provide a basis for a consequence analysis. In order to get a good perspective on the motives behind *unintentional* intrusion, this should therefore be investigated within the framework of *all* possible motives.

In a second step, the group reduced the number of parameters to seven, which was considered optimal based on the task and the organisation of the work. Three parameters were omitted:

- *Climate conditions* can be regarded as a dependent – it can be expressed indirectly in the geodemographic parameters *Human Settlement Pattern, General Scientific* and *Knowledge Level* and/or *Infrastructure*.
- *Infrastructure* is expressed indirectly under *Transportation System* and *Information System*.
- *Societal Supervision* was replaced by *Form of Society*, which the group considered to be a more well-defined parameter.

Range of conditions

For the identified variables the working group identified the following discrete conditions which the variable can express:

- **Human settlement pattern:** Geodemographic pattern at or near the repository location.
  - Megalopolis – Most people live in very large "modern" cities (e.g. New York City, Tokyo, Los Angeles).
  - X-city – most people live in cities and towns of various sizes[2] (roughly like Sweden today).
  - Sparse – Human settlements are spread out over a large area. "Sparse modern" (such as Iceland, Canada today) or "sparse unmodern" (roughly like Sweden some hundred years ago).
- **General scientific and knowledge level:** relative to the western world today.
  - Very high, but only among an elite.
  - Very high among the general public.
  - Roughly like today.
  - Much lower.
- **Transportation system:** relative to the western world today.
  - Greatly increased capacity (faster, more efficient, more reliable, more accessible, cheaper, cleaner).
  - Like today or slightly increased capacity.
  - Reduced capacity.
  - Decay – means that something causes things to develop in a negative direction. It may be war, environmental degradation and/or natural disasters that lay waste resources so that they cannot be restored, much less continue to develop positively. This may occur more or less dramatically, over a long or short span of time.
- **Information system:** relative to the western world today.
  - Greatly increased capacity.
  - Like today or slightly increased capacity.
  - Reduced capacity.
  - Decay (see above).
- **Knowledge of the repository:** Existence, properties and location.
  - Widely known.
  - Known only to an elite.
  - Known only locally (Example: The local population retains a "rumour" or a "myth" of the repository as a part of its local culture).
  - Lost.
- **Form of society:** Legitimacy of government and relative governability of society. Legitimacy describes to what extent the population gives approval and support to those in power. Governability describes to what extent the population obeys the laws and rules issued by those in power.
  - High legitimacy and governable social system.
  - High legitimacy and difficult-to-govern social system.
  - Low legitimacy and governable social system.
  - Low legitimacy and difficult-to-govern social system.
- **Purpose:** of disrupting the repository.
  - To bring up another resource than the radioactive waste or to build something in the rock (repository unknown).
  - To retrieve the waste as a resource or to relocate it.

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[2] "Rank size": there is a linear inverse relationship between size and number.

- To inspect the repository and its safety.
- To map and investigate the area (repository unknown).
- To sabotage the repository, commit extortion, etc, i.e. evil intent.

The final set of variables and ranges of conditions, the morphological field, devised by the group and used in the analysis is shown in Figure 5-2.

5.3 Analysis and societal scenarios

5.3.1 Analysis

The parameter space contains 15,360 formally possible configurations or framework scenarios, of which only a fraction are consistently cohesive, i.e. do not contain internal contradictions. Two of these framework scenarios, which represent two widely different futures, are shown in Figure 5-3 and Figure 5-4.

Human settlements (geodemo)	General scientific and knowledge level	Transportation system	Information system	Knowledge of repository	Form of society (legitimacy & governability)	Purpose of disruption
Megapolis	Very high among elite	Increased capacity	Increased capacity	Generally known	Legitimate Ungovernable	Get other resource/build
X-city	Generally high (much higher than today)	Like today	Like today	Known to elite	Legitimate Governable	Retrieve as resource
Sparse	Like today	Reduced capacity	Reduced capacity	Known locally (only)	Illegitimate Governable	Inspect repository
	Much lower than today	Decay	Decay	Lost	Illegitimate Ungovernable	Mapping/ investigation
						Sabotage

Figure 5-2. *The set of variables and ranges of conditions, the morphological field, used in the analysis.*

Human settlements (geodemo)	General scientific and knowledge level	Transportation system	Information system	Knowledge of repository	Form of society (legitimacy & governability)	Purpose of disruption
Megapolis	Very high among elite	Increased capacity	Increased capacity	Generally known	Legitimate Ungovernable	Get other resource/build
X-city	Generally high (much higher than today)	Like today	Like today	Known to elite	Legitimate Governable	Retrieve as resource
Sparse	Like today	Reduced capacity	Reduced capacity	Known locally (only)	Illegitimate Governable	Inspect repository
	Much lower than today	Decay	Decay	Lost	Illegitimate Ungovernable	Mapping/ investigation
						Sabotage

Figure 5-3. *A framework scenario that shows a pausible future of a continuously developing society.*

Human settlements (geodemo)	General scientific and knowledge level	Transportation system	Information system	Knowledge of repository	Form of society (legitimacy & governability)	Purpose of disruption
Megapolis	Very high among elite	Increased capacity	Increased capacity	Generally known	Legitimate Ungovernable	Get other resource/build
X-city	Generally high (much higher than today)	Like today	Like today	Known to elite	Legitimate Governable	Retrieve as resource
Sparse	Like today	Reduced capacity	Reduced capacity	Known locally (only)	Illegitimate Governable	Inspect repository
	Much lower than today	Decay	Decay	Lost	Illegitimate Ungovernable	Mapping/ investigation
						Sabotage

Figure 5-4. *A framework scenario that shows a plausible future that differs from the one in Figure 5-3.*

In the analysis, the morphological field is investigated for the purpose of finding internal relationships, patterns and consistent configurations. The investigation of the total number of internally consistent configurations, i.e. the solution space, showed that three variables dominated:

1. General scientific and knowledge level.
2. Knowledge of the repository's existence.
3. Intentionality with regard to disrupting the repository.

In the analysis of the framework scenarios identified by the group and the motivations and explanations to the scenarios, a new (fourth) variable was added that described the socio-technical development process as continuous or discontinuous. This parameter was identified as crucial for the development of the analysed parameters. An example of discontinuous development is when the society recovers after a near-total collapse. The field then assumed the appearance shown in Figure 5-5.

General scientific and knowledge level	Knowledge of repository	Purpose of disruption	Societal development process
Very high among elite	Generally known	Get other resource or build	Continuous
Generally high (much higher than today)	Known to elite	Retrieve as resource	Discontinuous
Like today	Known locally (only)	Inspect repository	
Much lower than today	Lost	Mapping/investigation	
		Sabotage	

Figure 5-5. *The morphological field after the analysis.*

5.3.2 The framework scenarios

In the solution space that was identified in the analysis four internally consistent framework scenarios concerned with unintentional disruption were identified. These scenarios are characterised below.

The inclined plane

The inclined plane is a scenario that describes a society in progressive decay. The general scientific and knowledge level is lower than in the Western World today. Knowledge of the repository is lost. In this society, the repository may be disrupted unintentionally. Something may be built in the rock next to the repository, for example in order to exploit a resource. Another purpose may be to drill boreholes to map or investigate the area.

The collapse

Collapse entails that a dramatic sequence of events has occurred and that we are in a period following a, possibly global, breakdown of society. The general knowledge level is lower than today, and knowledge of the repository is either lost or exists only locally in the form of a local culture based on myths and stories. In this society, as in "The inclined plane", the repository may be disrupted unintentionally. The purpose may be similar to in "The inclined plane", something is built in the rock close to the repository in order to bring up a resource other than the spent fuel or drilling is performed to map or investigate the area.

The recovery

Recovery entails that a dramatic sequence of events has occurred and that we are in a period following the collapse, or a discontinuity, in the evolution of society. In contrast to "The collapse", the society has been built up again. The general knowledge level is higher than in the Western World today. The knowledge of the repository has been lost, however. The purposes of the disruption are the same as in "The inclined plane" and "The collapse", but the consequences may be different.

General scientific and knowledge level	Knowledge of repository	Purpose of disruption	Societal development process
Very high among elite	Generally known	Get other resource or build	Continuous
Generally high (much higher than today)	Known to elite	Retrieve as resource	Discontinuous
Like today	Known locally (only)	Inspect repository	
Much lower than today	Lost	Mapping/investigation	
		Sabotage	

Figure 5-6. *The framework scenario "The inclined plane".*

General scientific and knowledge level	Knowledge of repository	Purpose of disruption	Societal development process
Very high among elite	Generally known	Get other resource or build	Continuous
Generally high (much higher than today)	Known to elite	Retrieve as resource	Discontinuous
Like today	Known locally (only)	Inspect repository	
Much lower than today	Lost	Mapping/investigation	
		Sabotage	

Figure 5-7. *The framework scenario ”The collapse”.*

General scientific and knowledge level	Knowledge of repository	Purpose of disruption	Societal development process
Very high among elite	Generally known	Get other resource or build	Continuous
Generally high (much higher than today)	Known to elite	Retrieve as resource	Discontinuous
Like today	Known locally (only)	Inspect repository	
Much lower than today	Lost	Mapping/investigation	
		Sabotage	

Figure 5-8. *The framework scenario ”The recovery”.*

Selective forgetfulness

Selective forgetfulness means that some knowledge has been lost, even though the overall knowledge level has increased. Owing to new, currently unknown or unspecified knowledge development, other specific knowledge areas may have fallen into disuse. Fission power and thereby current nuclear power technology is overshadowed by radically new energy technologies e.g. fusion power, photosynthesis, vacuum energy. Nuclear waste is no longer an important and debated issue, the repository site is abandoned and eventually the repository is forgotten.

General scientific and knowledge level	Knowledge of repository	Purpose of disruption	Societal development process
Very high among elite	Generally known	Get other resource or build	Continuous
Generally high (much higher than today)	Known to elite	Retrieve as resource	Discontinuous
Like today	Known locally (only)	Inspect repository	
Much lower than today	Lost	Mapping/investigation	
		Sabotage	

Figure 5-9. *The framework scenario "Selective forgetfulness".*

5.4 Conclusions from the societal analysis

Based on the application of morphological field analysis performed at Frösunda, 1998 the following conclusions were drawn:

- It is possible to find (imagine) internally consistent and feasible social scenarios where unintentional human actions may have an impact on the repository.
- It is difficult to imagine that continuous societal development with a high knowledge level could lead to unintentional intrusion in the repository, resulting in serious harm to society. However, this prospect cannot be entirely ruled out, since the long time span involved means that the knowledge level could change in a completely unexpected way; there is an unspecified uncertainty which causes a risk of "selective forgetfulness".
- In the long-term perspective, no institutions can guarantee the preservation of knowledge of the repository, regardless of whether society evolves in a positive or negative way. In the event of the collapse or slow decay of society, it is reasonable to assume that institutions will break down. In the event of collapse and recovery, there is also a risk that institutional knowledge will be lost.
- Not surprisingly, intentional human impact is a much wider and more complicated field of research than unintentional.

6 Scenarios considered in SR-Can

6.1 Ambiguities in selection of illustrative cases

Large uncertainties are associated with the development of technology and society. To avoid speculation the NEA working group on assessment of future human actions/OECD/NEA 1995a/, as well as SSI in the general guidelines to their regulations /SSI 2005/ suggest an approach based on present-day knowledge and experience. Another generally accepted premise is to only include unintentional FHA affecting the repository in design and safety assessment.

Analysis of societal factors is not considered meaningful on time perspectives longer than a maximum of 500 years. Not surprisingly this time frame coincidence with the maximum time active control of the repository can be assumed to be maintained. The performed analysis of societal conditions concluded that fundamental changes in society are required for unintentional disturbances of the repository to occur. These changes could be the result of some more or less dramatic evolution, or the result of a long time having passed since repository closure. Application of the combination of ongoing current practise with unintentional actions literally, the logical conclusion would be that inadvertent human actions yielding radiological consequences will not occur. Current activities at the candidate and similar sites will not impact on repository safety. Drilling to great depth is solely performed to investigate the possibility of locating a repository for spent nuclear fuel at the candidate sites.

There is another dilemma in the description of scenarios based on human actions. In order to quantify the consequences, detailed descriptions of the human actions are required. This will inevitably include assumptions that can be regarded as pure speculations and questioned. However, both the technical and societal analyses, even if they do not depict conditions that actually exist today, can be said to be based on current practise and knowledge, and their results can be used for the selection of representative cases and contexts. The selected cases, societal contexts and the scenarios they make up are not based on current practise in the sense that they might occur today. They are rather, as stated by the NEA working group "*representations of potential realities based on a set of assumptions*". When describing scenarios based on the selected cases speculations are avoided by assuming the most severe combination of course of events from simplified and plausible alternatives.

6.2 Scenario selection

It is probable that the repository site will be used by people in the future. Human actions that influence radiological safety and are carried out without knowledge of the repository and/or its purpose cannot be ruled out. The technical analysis gives examples of human activities that can impact the repository safety. From the societal analysis, it is concluded that is possible to find (imagine) internally consistent and feasible social scenarios in which unintentional human actions may have an impact on the repository. The results from the technical analysis are the starting point for the selection of representative cases. The actions with the greatest potential to impact the safety of the repository, i.e. actions that disrupt barrier safety functions, are chosen. It is then investigated whether these actions can be combined with the societal contexts to form scenarios "*based on present living habits and technical prerequisites*" as stated in SSI's general guidelines to their regulations /SSI 2005/. Actions that influence the isolation or the function indicators for isolation are the most severe, followed by actions that influence retardation or the function indicators for retardation. Changes in land use may result in an increase of the doses to which human beings may be exposed if the isolation has been compromised and there are leaking canisters in the repository.

The repository will be situated at 400–700 metres depth in the rock. The reason for this is the wish to locate the repository in an environment where the isolation of the fuel will be retained even in the event of extensive changes on the surface. Changes that have been considered in repository design are natural changes and changes caused by man. Examples of natural changes are change of the repository's location in relation to the sea, and the presence of permafrost and ice sheets. Examples of considered human actions are extraction of water and alternative generally occurring land uses and facilities. The natural changes will influence human actions and settlement, as well as society and man's opportunities or preferences to use the repository site.

All of the actions listed in Table 4-1 influence the migration of radionuclides in the biosphere. However, actions that are performed on or near the surface, down to a depth of a few tens of metres, are judged not to be able to affect the engineered barriers and the isolation of the fuel. This applies to the actions T4, H2, H3, H4, H5, H6, H7, H8, M3, M4, C2, C3, C4 and C5 (though some of them could include drilling of relatively deep wells, this issue is adequately covered by the other categories considered). Activities near the surface that belong to categories M and H are deemed to have less influence on the repository than natural changes in conjunction with future climate change. Of the actions that entail a chemical influence (C2–C5), acidification of air and land (C3) has been studied in most detail. In realistic cases of acidification by atmospheric sulphur and carbon dioxide, the environment at repository depth is not affected /Nebot and Bruno 1991, Wersin et al. 1994/. Soil layers and bedrock are judged to work efficiently as both filter and buffer against other chemical compounds as well.

Bombing or blasting on the ground surface above the repository (M5) cannot affect the isolation of the waste. Blasting of nuclear weapons would have a mechanical impact on the bedrock but even if the bombs were to be very powerful it is probable that the isolation of the spent fuel would remain unaffected. Further such an event implies a nuclear war and the consequences of the war and the blast itself would be much greater than the consequence of the hypothetical leakage from the repository. Sub-surface testing of nuclear bombs (M6) close to the repository may however violate the isolation in a similar way to an earthquake. The test would need to be carried out close to the deposited canisters. Testing of bombs could be combined with "The recovery" to form a plausible scenario. However tests of bombs are carried out below the surface to avoid environmental impact, and also require knowledge of nuclear fission and fission products and the risks associated with them. Measurements are carried out in connections with the tests, and if a detectable leakage from the repository were to exist it most probably would be distinguished from the releases from the bomb and most likely handled by a society performing sub-surface weapon tests.

Some of the actions in Table 4-1 can – besides influencing radionuclide transport – indirectly influence the isolation of the waste if they affect the geosphere's capability to provide favourable hydrological or chemical conditions. Such actions would have to be performed directly above or very close to the deep repository and include drilling and/or construction in the rock (M1, M2). These categories include actions that have to do with heat extraction (T1, T2, T3), well drilling (H1) and disposal of hazardous waste in the rock (C1). Hydropower plants (H5) and open-cast mines and quarries (M3) may also involve drilling or rock works at great depth. Before a rock facility is built, drilling is carried out to investigate the rock. What all of these cases share is therefore that – if present day technology is applied – they involve drilling in the rock.

Large rock facilities adjacent to the repository are deemed to be out of the question in a short time perspective, i.e. within a few hundred years, for several reasons. For example, the deep repository is itself a large rock facility – the only one of its kind in Sweden – that is very unlikely to be forgotten over such a short time span. Institutional control can be expected to endure on this timescale. The enumerated actions that encompass major rock works are less likely at the repository sites, based on current technology and economics. In a slightly longer time perspective, i.e. a few or several hundred years or more, it is difficult to predict how knowledge, technology and society will develop, and thereby how, where and why rock facilities will be built. Based on current practice, rock facilities at depth down to around 50 metres may very well occur and actually exist at both candidate sites (the SFR facility at Forsmark and the Clab facility at Oskarshamn). In the far future, the potential ore resources to the north of the investigated area in Forsmark may be exploited.

Of the actions in Table 4-1, "Drill in the rock" is judged to be the only one that can directly lead to penetration of the copper canister and breach of waste isolation, while at the same time being inadvertent, technically possible, practically feasible and plausible. "Drill in the rock" is furthermore a conceivable action in the light of the results of the societal analysis. Even if it is possible to build a rock cavern, tunnel or shaft or to excavate an open-cast mine which leads to penetration of the copper canister, doing so without having investigated the rock in such a way that the repository is discovered, i.e. without knowledge of the repository, is not deemed to be technically plausible. However the construction of a rock facility at shallow depth or a mine in the vicinity of the Forsmark site may occur in the future. The cases "Canister penetration by drilling" and "Rock facility in the vicinity of the repository" and "Mine in the vicinity of the Forsmark site" have therefore been selected for further description and analysis in the **Main report**.

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Appendix A

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