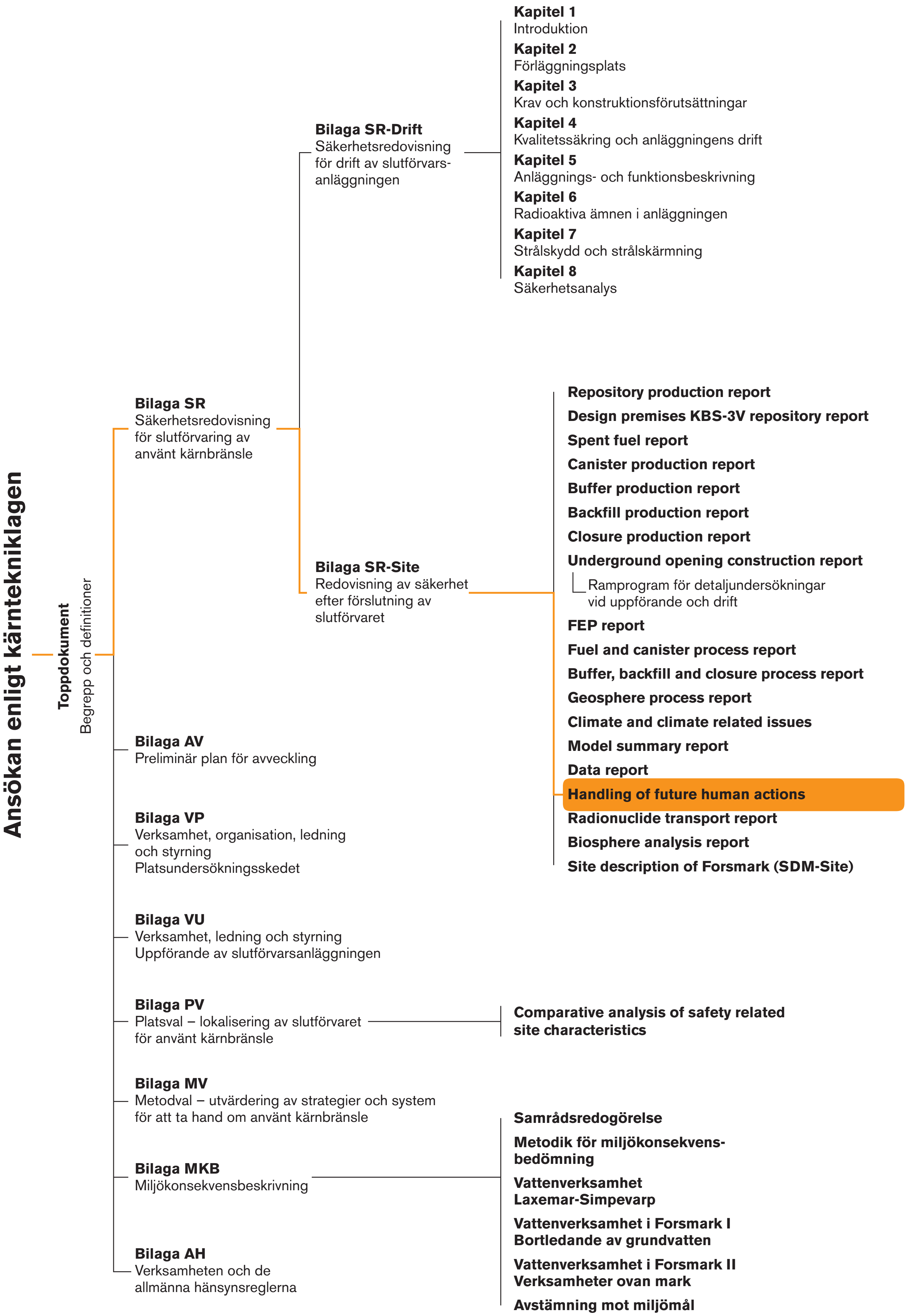

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Technical Report

TR-10-53

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

Svensk Kärnbränslehantering AB

December 2010

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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-Site, which is a safety assessment in support of the license application for a final repository in Sweden.

This report is an update of the preceding report SKB TR-06-24 which was issued in support of the safety assessment SR-Can made in preparation for SR-Site. The preceding report SKB TR-06-24 mainly built on translations from Swedish of the report SKB R-98-54, that supported an earlier safety assessment of a KBS-3 repository in 1999. The Swedish report from 1998, which was first to outline the strategy that SKB follows in these matters, was edited by Lena Morén and co-authors were Tom Ritchey and Maria Stenström, Swedish Defence Research Agency. The translation was reviewed by Tom Ritchey.

This updated version of the report has been edited by Fred Karlsson, SKB (Chapters 1 to 5) and Kristina Skagius, Kemakta (Chapter 6), who also has been the main editor of the report assisted by Johan Andersson. Contributions to the analyses of the selected illustrative cases reported in Chapter 6 have been provided by Patrik Sellin, Jan-Olof Selroos, Ignasi Puigdomenech, Tobias Lindborg, Björn Gylling, SKB, Sven Follin, SF Geologic, Per-Gustaf Åstrand, Facilia, and Niko Marsic, Kemakta.

The report has been reviewed by Alan Hooper, Alan Hooper Consulting Ltd, UK and Mike Thorne, Mike Thorne and Associates Ltd, UK.

Stockholm, December 2010

Allan Hedin

Project leader SR-Site

Summary

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-Site (see further the Main report /SKB 2011/). The purpose of this report is to provide an account of general considerations concerning FHA, the methodology applied in SR-Site to assess FHA, the aspects of FHA needed to be considered in the evaluation of their impact on a deep geological repository and to select and analyse representative scenarios for illustrative consequence analysis. The main focus of this report is a time period when institutional control has ceased to be effective, thereby permitting inadvertent intrusion. However, a brief discussion of the earlier period when the repository has been closed, sealed and continuously kept under institutional control is also provided.

General

The potential exposure to large quantities of radiotoxic material is an inescapable consequence of the deposition of spent nuclear fuel in a final repository, and consequently intrusion into the repository needs to be considered in repository design and safety assessment. In accordance with ICRP recommendations /ICRP 2000/, intrusion in the post-closure phase of institutional control and beyond is primarily prevented through the design of the repository. In addition to that there will presumably continue to be safeguards measures, preservation of information (record keeping) and possibly some sort of markers placed at the site. During the institutional control period, activities at the site have to be restricted or directed if they have the potential to interfere with or hinder surveillance of the site, but this does not necessarily rule out all forms of access to the area. Also the fact that the repository contains fissile materials is an important aspect. Control of safeguards measures will most likely be upheld by national as well as international agencies. Furthermore, the authorities in their review of SR-Can /Dverstorp and Strömberg 2008/ maintain that the state, rather than SKB, is expected to be responsible for the supervision and monitoring of the repository after sealing.

Man is dependent on, and influences, the environment in which he lives. After the repository has been closed, future generations should be able to utilise the repository site according to their needs without jeopardising their health. In the case of a final repository of the KBS-3 type, there are, however, inevitably examples of activities that, if carried out carelessly or without knowledge of the repository, could result in exposure to radiotoxic elements from the spent fuel. Therefore, there is an international consensus that future human activities shall be considered in safety assessments of deep geological repositories. Based on generally accepted principles and the Swedish Radiation Safety Authority's, SSM's, regulations SSM FS 2008:21and SSM FS 2008:37, the future human actions considered in this part of the safety assessment are restricted to global pollution and actions that:

- are carried out after the sealing of the repository,
- take place at or close to the repository site,
- are unintentional, i.e. are carried out when the location of the repository is unknown, its purpose forgotten or the consequences of the action are unknown,
- impair the safety functions of the repository's barriers.

However, in line with SSM's general guidance /SSM 2008a/, future human actions and their impact on the repository are evaluated separately, and are not included in the main scenario reference evolution or in the risk summation.

Systematic approach

For the purpose of providing as comprehensive a picture as possible of different human actions that may impact the deep repository as well as their background and purpose, the following systematic approach has been used:

- *Technical analysis:* Identify human actions that may impact the safety functions of the repository. Describe and, in technical terms, justify that such actions may occur.
- *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.
- *Choice of representative cases:* The results of the technical and societal analyses are put together. One or several illustrative cases of future human activities are chosen.
- *Scenario description and consequence analysis of the chosen cases.*

The technical analysis was based on the results from a workshop carried out within the framework of SR 97 /Morén et al. 1998/. For SR-Can, the relevance of the results from the workshop regarding recent technical developments was reviewed based on consultation with technical experts within SKB. Complementary FEP work conducted for SR-Site did not result in any modifications to the list of human actions developed for SR-Can. The technical analysis concludes that actions that include drilling and/or construction in rock are those with the greatest potential influence on the repository. Furthermore, the repository site was regarded as more favourable than other locations for building a heat store or heat pump plant, due to the heat generated by the spent fuel. For the other actions, the repository site was considered to be equivalent to, or less favourable than, other places with similar bedrock.

The study of societal aspects concludes that it is difficult to imagine inadvertent intrusion, given a continuous development of society and knowledge. However, owing to the long time horizon, it is not possible to rule out the possibility that the repository and its purpose will be forgotten, even if both society and knowledge make gradual progress. Nor is it possible to guarantee that institutional control over the repository site will be retained in a long time perspective.

Choice of representative cases

A first set of representative cases consider the situation when the repository is sealed. It is probable that the repository site will be used by utilised 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. Actions that influence the containment or the function indicators for containment are the most severe, followed by actions that influence retardation or the function indicators for retardation.

Out of all potential actions considered in the assessment, only "Drill in the rock" is judged to be the one that can lead directly to penetration of the copper canister and breach of waste containment while at the same time being inadvertent, technically possible, practically feasible and plausible. 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 considered 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. Therefore, the cases "*Canister penetration by drilling*" and "*Rock facility in the vicinity of the repository*" and "*Mine in the vicinity of the Forsmark site*" were selected as representative cases for scenarios related to a sealed repository, and which should be further described and analysed.

According to regulations, it is also necessary to define and analyse a case that illustrates the consequences of an unsealed repository. Since the repository is gradually excavated and operated, the case selected for analysis is representing an *incompletely sealed repository* rather than an unsealed repository. Abandoning the repository in the middle of the process of backfilling a deposition tunnel is judged as rather unlikely because this would mean that canisters are left at the surface where they would constitute a larger risk than if emplaced in the repository. It is judged more plausible that the repository is abandoned when all canisters are deposited and all deposition tunnels backfilled and sealed, but with all other repository volumes still open.

Canister penetration by drilling

In the drilling case, it is assumed that technology to drill to great depth is available, that the knowledge of the location and purpose of the repository is lost, that the intruders are incapable of analysing and understanding what they have found and that no societal regulations on drilling exist. It is assumed that an evolution rendering this situation will require some time. Based on this, it is assumed that the drilling will take place 300 years or longer after repository closure. It is also assumed that the purpose of the drilling is to reach great depth. The drilling angle is assumed to be 85° and the cuttings are assumed to be spread on the ground. The site and the borehole are abandoned without further measures. About a month later, a family moves to the site and operates a domestic production farm there. The abandoned borehole is used as a well by the family. The consequences for the repository and the annual effective doses to the family as well as the dose to the drilling personnel are assessed.

The dose rate that a member of the drilling personnel would be exposed to while working in the highly contaminated area 300 years after repository closure is calculated to 500 mSv/hour. If drilling occurs at c 5,000 years after repository closure, the dose rate has decreased to values below 1 mSv/hour. These calculated dose rates are very high and is primarily a result of the cautious assumption regarding the amount of Ag-108m brought to the surface when drilling. In case Ag-108m would not be instantaneously released, 3 percent instead of 100 percent of the inventory of Ag-108m would be brought to the surface when drilling. Due to the total dominance of Ag-108m to the dose rate, this would reduce the dose rate to workers to 3 pecent of the value, i.e. the dose rate 300 years after repository closure would be about 15 mSv/hour. The dose to the family that settles on the site originates from two sources. The total dose from using the borehole as a well 300 years after repository closure is 0.24 mSv/year and is dominated by the contribution from Am-241. The maximum total annual effective dose from the use of the contaminated soil for agricultural purposes is about 7 Sv/year and this dose is obtained 300 years after repository closure. The dose is dominated by ingestion of vegetables contaminated with Tc-99 and there is also a significant dose contribution due to external radiation from Ag-108m. The calculated annual dose is very high, but it should be noted that there are a number of simplified, cautious assumptions made in the calculations.

The impact of an open borehole on the groundwater flow in the repository and the surrounding rock has been studied by introducing boreholes at various locations in the hydrogeological base case model applied for analyses of the temperate period in SR-Site. Although the flow paths are affected by the borehole, the results show only small effects of the borehole, indicating that the flow paths established by the presence of the borehole have similar transport characteristics as the flow paths without a borehole. An open borehole might affect the long-term properties of the backfill in the deposition tunnel in the vicinity of the borehole but the effect on the backfill above neighbouring deposition holes is assessed as negligible.

Rock excavation or tunnel case

A tunnel constructed at 50 metres depth with a cross section of 100 square metres and with a length corresponding to the whole repository footprint along the centre line of the deposition areas is considered. The justification of this assumption is that it is plausible in relation to current practice and does not underestimate the possible impact on the repository. As in the drilling case, it is assumed that the existence of the repository is forgotten and that the technical standards for making underground constructions are similar to those used at the present. Further, it is assumed that the construction of the rock excavation (tunnel) is not initiated before 300 years after repository closure.

At Forsmark, the upper part of the bedrock (down to about 150 metres depth) in the target volume for the repository is much more water conductive than the lower part, especially below 400 metres depth. The assessment indicates that the upper 150 metres of the bedrock above the repository is an unfavourable location for a tunnel from en engineering point of view, due to the exceptionally high water yield in this part of the bedrock. These conditions also imply that a tunnel constructed in this part of the bedrock would not affect the groundwater flow at repository depth such that the presence of the tunnel violates the safety functions of the deep repository. The design consideration to locate the repository to a depth that allows utilisation of the site for generally occurring future human activities should, therefore, be fulfilled at Forsmark.

Mine in the vicinity of the Forsmark site

The ore potential at Forsmark has been analysed within the site investigations. In an area south-west of the Forsmark site a felsitic to metavolcanic rock, judged to have a potential for iron oxide mineralisation, has been identified /Lindroos et al. 2004/, but is assessed to be of no economic value. Nevertheless, as this judgement may be revised in the future due to economical reasons, the potential exploitation of this mineralisation is addressed. The assessment indicates that exploitation of the potential mineral resources in the vicinity of the Forsmark site would not impact the safety functions of the repository. The design consideration to locate the repository at a site without natural resources is, therefore, considered to be fulfilled.

Incompletely sealed repository

The basic assumption in the case selected as representative for scenarios related to an unsealed or incompletely sealed repository is that the repository is abandoned when all canisters are deposited and all deposition tunnels backfilled and sealed, but the main and transport tunnels as well as the central area, repository access (ramp and shafts) and the ventilation shafts in the deposition area are still open.

The simplified analyses carried out demonstrate that abandoning the repository without backfilling and sealing all parts of the repository may imply that backfill in the deposition tunnels are lost and that the safety functions for containment are violated for deposition holes located close to the entrance of the deposition tunnels. Therefore, the general conclusion is that the repository should not be abandoned prior to complete backfilling and sealing.

The analyses of a not completely sealed repository further demonstrate that the repository system adapted to the Forsmark site is robust over a long period of time. Even without backfill in parts of the system, no canister failures are expected as long as diffusion dominates the transport of corrosive species in the backfill in deposition tunnels and buffer in deposition holes. The hydrogeological results for temperate conditions also indicate only small effects of the open tunnels on the Darcy flux at deposition hole positions. Although the open tunnels change the flow paths with somewhat reduced flow related transport resistances in the rock as a result, these resistances are still high. The fact that flow paths are captured by the open tunnels and discharge through the shafts and ramp above the central area is also considered as insignificant, since discharge points occur close to the repository also in the reference evolution and also because periglacial conditions with permafrost in the upper parts of the ramp and shafts will prevail for large parts of the 58,000 year time period. This implies that the impact of the open tunnels for deposition holes other than those directly affected by the expanding tunnel backfill is small.

If corrosion breakthrough in canisters occurs during the next period with glacial conditions, i.e. from 58,000 years to 66,200 years after present according to the reference evolution, the annual effective dose from radionuclides in the failed canisters will exceed the regulatory risk limit. However, as long as the number of failed canisters is limited to less than c. 20, the effective dose from radionuclides in these canisters will be lower than the dose obtained from background radiation. Considering the large uncertainties and cautious assumptions made in the analysis, the calculated annual effective dose should be seen as an illustration of possible consequences rather than an estimation of what the consequence would be if the repository is not completely backfilled and sealed.

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-Site (see further the Main report /SKB 2011/).

The purpose of this report is to provide an account of the following.

- General considerations concerning FHA.
- The methodology applied in SR-Site 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 /SKB 2011/and the FEP report (Features events and processes report) /SKB 2010a/ the content of this report has been audited by comparison with FEP databases compiled in other assessment projects.

The main focus of this report is a time when institutional control has ceased to be effective thereby permitting inadvertent intrusion. However, a brief discussion of the earlier period when the repository has been closed, sealed and is being continuously kept under institutional control is provided in Section 2.4.

1.2 Previous work

In their review of SKB's programme for research, development and demonstration from 1995 /SKB 1995/, the Swedish Nuclear Power Inspectorate, SKI, pointed out that SKB:

"... must develop their own strategy for how issues relating to human intrusion should be handled in future safety assessments." /SKI 1996, p 87/

SKI further stated that the work performed within OECD/NEA (Organisation for Economic Co-operation and Development/Nuclear Energy Agency) /NEA 1995a/ was an adequate basis for the development of 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 multi-faceted question of FHA, an ambition was to, in line with the NEA working group recommendations, involve people active within a broad spectrum of relevant fields in the development of a strategy /NEA 1995a/. 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 /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.

The experts participating at the workshops at Skebo, IVA and Frösunda, 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 workshop participants, to the development of the strategy. In addition to this, they contributed the methodology applied in the analysis of societal conditions. Furthermore, they both organised and reported the workshop on societal aspects at Frösunda. This work on societal aspects is presented again in Chapter 5 of this report.

The FHA-study from 1998, used for the safety assessment SR 97, was later translated from Swedish to English and updated prior to the next safety assessment of spent fuel disposal SR-Can /SKB 2006a, b/. The review of SR-97, by the authorities and their international group of experts /SKI 2000, 2001/, was referred to and considered in the updated FHA-report issued in 2006. Not least the strategy to handle FHA was modified as a result of the reviewers' comments. The development of the strategy for FHA is further described in Chapter 3 of this report.

The safety assessment SR-Can illustrated human intrusion by presenting and evaluating three different illustrative cases. This was commented by the authorities in their review of SR-Can /Dverstorp and Strömberg 2008/. Further modifications of this approach have been made for SR-Site, as a result of the review comments. This development is presented in Chapter 6 of this report. The illustrative cases themselves were modified and another notable difference from SR-Can is that the FHA-cases are now presented here in Chapter 6 and not only in the main report of SR-Site.

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 /NEA 1995a/ and ICRP Publication 81 /ICRP 2000/.

2.1 Waste management principles

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

- convert 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 2000/.

- 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 2000/.

2.2 Responsibilities between generations

There is an international consensus, e.g. /IAEA 1995, 1997, 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 reasonably 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 defines 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[1], 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 programme 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. This is referred to as "reversibility". 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.

Descriptions of ongoing local human activities and land use are included in the biosphere part of the site description 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 site is 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 in the identification of critical groups, see further the SR-Site ecosystem reports /Andersson 2010, Aquilonius 2010, Löfgren 2010/ and the biosphere synthesis report /SKB 2010b/.

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[1] Actions taken to limit the proliferation of nuclear weapon in accordance with the Nuclear Non-Proliferation Treaty (NPT)

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. Major climate changes are expected in the time perspective of the long-term safety assessment. 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 hundreds 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. Therefore, the emission of greenhouse gases is not included among FHA considered in this report, whereas 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 /NEA 1995a/ and of the ICRP /ICRP 2000/ are local, post-closure actions with potential impact on the final repository. It is also this kind of actions that the Swedish Radiation Safety Authority, SSM, mentions in its regulations and guidelines /SSM 2008b/. 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.

2.4 Intrusion during institutional control period

The authorities consider in their review of SR-Can that SKB should produce more detailed proposals for measures during the period of institutional control including land use restrictions and discuss how these affect the probability of early unintentional intrusion /Dverstorp and Strömberg 2008/. Prevention of intrusion during the operational phase of the repository is ensured through the physical protection of the facility. In addition, there will be safeguard measures and preservation of information during the operational period and the period of institutional control. Intrusion in the post-closure phase of institutional control and beyond is primarily prevented through the design of the repository. In addition to that there will presumably continue to be safeguards measures, preservation of information (record keeping) and possibly some sort of markers placed at the site. Ideas of how safeguarding of the repository could be facilitated have been presented in a study reported by the authorities /Fritzell 2006/. Possible ways of arranging this in satisfactory way were discussed. It should work for long periods of time and not be dependent on physical access to the waste to verify its presence in the repository. An efficient way of checking that the waste is kept in the repository and no illegal attempts of intrusion are made would be satellite monitoring of the site. Visible, infrared and radar imaging are existing techniques. For example, radar can detect changes at the site with a resolution of a few metres, even at night and through clouds /Fritzell 2006, pp 9–10/. Satellite monitoring techniques can be utilised independently by both national and international agencies. For the time being it is difficult to be more specific than that. Measures to be taken for the post- closure period will most likely be included in the future planning of the closure and sealing of the repository.

The presence of a repository underground will require restrictions to be placed on activities at the site. Intrusion or anything else that can potentially harm the repository should be prohibited. However, that does not necessarily rule out all forms of access to the area. Merely staying at the ground surface above the repository, picking berries and mushrooms, hunting, farming etc. should not be harmful to either the health of those concerned or the integrity of the repository. On the other hand, construction of houses and roads, and even seemingly harmless activities like, for example, camping and forestry may have to be restricted or directed if they have the potential to interfere with or hinder surveillance of the site.

The fact that the repository contains fissile materials is an important aspect. Regarding today's situation, control of safeguards measures will most likely be required by national as well as international agencies (SSM, IAEA and Euratom) /Fritzell 2006, pp 11–14/. The authorities in their review of SR-Can /Dverstorp and Strömberg 2008/ maintain that the state, rather than SKB, is expected to be responsible for the supervision and monitoring of the repository after sealing, /SKI 2006/.

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 /SKB 1999/. It was outlined based on the conclusions of the NEA working group on assessment of future human actions at radioactive waste disposal sites /NEA 1995a/ and the results from the workshop at Skebo in December 1997. This and the suggested strategy were reported in 1998 /Morén et al. 1998/.

The Swedish radiation protection authority, SSI, issued its "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/. The Swedish nuclear power inspectorate, SKI, later issued its "Regulations concerning Safety in connection with the Disposal of Nuclear Material and Nuclear Waste" /SKI 2002/. SKI's general recommendations concerning the application of their regulations and SSI's background and comments to its regulations, as well as the general guidelines to SSI's regulations provided in 2005 include some recommendations as to the handling of FHA in the safety assessment /SSI 2005/. These documents, as well as ICRP Publication 81 /ICRP 2000/ were taken into account by SKB to produce a new report in support of the post-closure safety assessment SR-Can /SKB 2006a/. Also considered were SKI's and SSI's review comments and the viewpoints of international reviewers of SR 97 /SKI 2000, 2001/. Another document that was reviewed and dealt with in the updated version of the SR 97 strategy was "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 were also taken into account. The updated report on SKB strategy to handle FHA in support of SR-Can was issued in 2006 /SKB 2006b/.

Since then, the Swedish Radiation Safety Authority, SSM, has replaced both SSI and SKI. SSM has recently issued its regulations concerning safety in connection with the disposal of nuclear material and nuclear waste, including general recommendations concerning the application of the regulations /SSM 2008a/. SSM has also issued regulations on the protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste, together with general recommendations concerning the application /SSM 2008b/. This in itself does not warrant a revaluation since the content is the same in these regulations as in the earlier versions. However, more importantly, the authorities and their experts have reported their review of SR-Can /Dverstorp and Strömberg 2008/. The review comments on the treatment of future human actions scenarios have been considered in the handling of FHA in the safety assessment SR-Site and the results included in the present report, which is intended as an updated version of the SR-Can report on handling of FHA.

The authorities in their review of SR-Can takes up a number of excerpts from international documents with guidelines on how intrusion should be dealt with in safety assessment /Dverstorp and Strömberg 2008, Appendix 3/. A common denominator is that the required reporting only refers to unintentional cases /NEA 1995a, IAEA 1995, ICRP 1998, US EPA 1985, 2001, NRC 1995, UK EA 1993/. To these reports can be added the recent position paper issued by a German multi-agency working group on scenario development /Working Group on Scenario Development 2008/. The working group's position is clearly stated and much in line with international developments. They conclude that human intrusion cannot be excluded and should be dealt with in the safety case, but separately. Only inadvertent intrusion should be addressed and only after a certain time when institutional control is assumed to have been lost (the working group assumed 500 years). If possible, measures should be taken to prevent intrusion, but these measures must not impair the safety of the repository. Human intrusion scenarios should be evaluated with the aim to select measures that reduce their consequences. To evaluate the consequences of human intrusion by means of radiological limit values is not considered reasonable. The scenarios analysed need not be exhaustive or pessimistic. The German working group concludes by stating that boundary conditions for deriving human intrusion scenarios should be established in regulations.

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, in technical terms, justify that such actions may occur.

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, the workshop at Skebo and SSM's regulations of importance for the development and application of the strategy are summarised below /NEA 1995a, Morén et al. 1998, SSM 2008a, b/.

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 FHAs 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 select, justify and describe 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 utilised 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 – containment 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 identifying and describing a set of cases selected for their potential impact on the safety of the repository. Regarding the safety function isolation from humans, it may also be noted that this report is concerned with cases where FHA effectively compromises this function although the location and design of the repository does much to prevent this.

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 the combination of these that are most significant for repository safety. 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 SSM's regulations and recommendations

In its regulations SSMFS 2008:37, SSM states that "*the consequences of intrusion into a repository shall be reported*" /SSM 2008b/. 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 SSMFS 2008:37 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 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 ...*" However, according to SSMFS 2008:37 *"direct consequences for those individuals who intrude into the repository need not be accounted for."*

In the general recommendations to its regulations SSMFS 2008:21, SSM says that impact of future human activities, such as damage inflicted on the repository barriers, should be included in the category "*less probable scenarios*" /SSM 2008a/. 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*".

Further according to SSMFS 2008:21, "…*cases to illustrate damage to humans intruding into the repository as well as cases to illustrate the consequences of an unclosed repository that is not monitored"* should be included in the *"residual scenarios"*. The residual scenarios *"should include sequences of events and conditions that are selected and studied independently of probabilities in order to, inter alia, illustrate the significance of individual barriers and barrier functions."*

SSM's regulations in these matters mainly affect the application of the strategy and the account of FHA and their consequences in the safety assessment.

The direction of SSMFS 2008:37 that *"direct consequences for those individuals who intrude into the repository need not be accounted for"* is obviously not in agreement with that of SSMFS 2008:21 where "…*cases to illustrate damage to humans intruding into the repository…"* should be included in the residual scenarios. However, in their review of SR-Can the authorities state that there should be *"...a stylised calculation of the injuries to human beings who intrude into the repository"* /Dverstorp and Strömberg 2008, Section 14.2 page 105/. This direction has consequently been followed here in support of the new safety assessment SR-Site.

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. For SR-Can, the results from the workshop were 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 were also audited and compared with FEPs (Features, Events, Processes) related to FHA compiled in the NEA FEP database. For SR-Site, the FEP audit was revisited and updated. This is further described in the SR-Site FEP report /SKB 2010a/, where also the result of the audit is documented. The complementary FEP work conducted for SR-Site did not result in any modifications to the list of human actions developed for SR-Can. Therefore, the technical analysis conducted for SR-Can, which is described in the following subsection, is judged applicable also for SR-Site.

4.1.2 Methodology

The technical analysis was in line with the recommendations made by the NEA working group and SSI, 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 in SR-Can were used. The functions and function indicators are described in the SR-Can report /SKB 2006a, Chapter 7/.

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 utilise 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 for SR-Can /SKB 2006c, d, e/ 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 that were 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 was 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 were identified.

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 containment 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 utilisation 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 utilising it. Technological development can be driven by the high value of a resource. Thus, economics and technology are linked.

4.3 Future human actions that may impact the repository

Human actions that can affect the repository, divided into THMC categories, are given in Table 4-1. 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 plant*
	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: Excavate open-cast mine or quarry*
	M4: Construct dump or landfill
	M5: Bomb or blast on the surface above the repository
	M6: Subsurface bomb or blast*
Chemical impact	C1: Store/dispose hazardous waste in the rock*
	C2: Construct sanitary landfill (refuse tip)
	C3: Acidify air, water, soil and bedrock
	C4: Sterilise soil
	C5: Cause accident resulting in chemical contamination

*Includes or may include drilling and/or construction of rock cavern.

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). The 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 of water, 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 utilised for space heating.

Since the temperature in the rock is not very high (11–12°C at a depth of 500 metres at Forsmark /SKB 2008/), 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 1.3°C per 100 metres at Forsmark /SKB 2008/. The presence of the repository will result in an increased gradient. According to modelling results of the thermal response of the deep repository, the maximum increase at 100 m depth is approximately 4°C after 1,000 years /Hökmark et al. 2010, Chapter 5/. This heat anomaly would be detectable 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 utilised 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 optimisation 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 containment may fail if a canister is penetrated, see further Section 4.6.1. The heat storage facility may affect the capability of the geosphere 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 and/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 utilised 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. 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 capability of the geosphere 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 investigated Forsmark and Laxemar sites, such high temperatures are expected at depths of 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 today, but no systems at such great depths as would be required at places like Forsmark. In a system for extraction of geothermal heat, at least two boreholes are drilled and connected *via* a fracture system. Water is pumped down on one side of the fracture system and up on the other side. The water is heated as it passes through the fracture system. Systems of this type exist in areas where the temperature increases rapidly with depth. However, as already stated, no system exists today at the great depths that would be required at Forsmark. There are only a few boreholes in the world that are 8,000-10,000 metres deep or deeper. They are drilled for exploratory purposes. If geothermal energy were to be utilised at Forsmark, drilling techniques would have to be developed substantially to make this a routine technological activity.

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 fracture frequency and transmissivity, but the impact on the capability of the geosphere 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. Also, the drilling for geothermal energy is not necessarily followed by any installation for heat extraction. Even a failed geothermal project may have involved exploration drilling.

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. Saline water is always present at great depth, whereas fresh water is found closer to the surface. The depth to saline 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, primarily adjacent to the well. 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 impacts on the capacity of the rock to provide favourable hydrological and transport conditions are judged to be insignificant, as the effects are not expected to propagate to repository 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 judged desirable.

Technology

People have been utilising, 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 Section 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 pressurised 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, a reservoir or a surface water body. Surface water can be utilised 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 utilised by people is an important part of the biosphere description, see e.g. the SR-Site biosphere synthesis report /SKB 2010b/.

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

Exploration for mineral deposits in the Forsmark region cannot be excluded. The evaluation of the potential for ore and industrial minerals in the Forsmark area /Lindroos et al. 2004/ shows that the host rock where the repository is located is virtually sterile from an ore point of view. However, the surrounding area contains several minor mineralisations that might be explored in the future. Such explorations could also include the host rock volume at Forsmark.

Mineral exploration normally begins with airborne and surface investigations followed by drilling on targets of interest. The repository comprises a heterogeneity in the rock. A study has been made of the possibility to detect the repository by state of the art surface exploration methods /Isaksson et al. 2010/. The purpose was to evaluate if future exploration results could motivate drilling to repository depth. The study shows that the repository would not cause measurable responses in excess of instrumental or geologic noise for gravity, magnetic, electric and electromagnetic exploration methods. The repository is, however, expected to be detectable by seismic reflection surveys due to the lower seismic velocity of the backfilled tunnels. A low velocity reflector is likely to be interpreted as a deformation (fracture) zone and is not likely to motivate drilling.

The thermal response from the repository during the few thousand years is detectable from temperature measurements in relatively short boreholes (less than 100 m). This could possibly motivate drilling to larger depths.

Hence, drilling one or more boreholes to investigate the properties of the bedrock at great depth in Forsmark for mineral exploration purposes is less likely but cannot be excluded. If a major rock excavation project were to be undertaken several holes would be drilled to investigate the rock in the vicinity of the intended facility. The depth of such holes would depend on the intended depth of the facility. 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 ramp and shafts that extend to the surface are likely to be detected and may, if information on the existence of the repository has been partially or completely lost, arouse curiosity and exploration efforts. The predictions of actions following this discovery are of course speculative. The deviation in seismic and thermal responses may motivate investigations by drilling even if the most probable action would be excavation of the backfill material in the ramp or shafts.

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 pulverised by a device that strikes, twists and crushes. The pulverised 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. 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 the heterogeneity that the tunnels, buffer and canister comprise will be discovered if they are hit. 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 containment of the spent nuclear fuel. 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 containment of the spent fuel is breached, the borehole will be a transport pathway for radionuclides. The capacity of the rock 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 the borehole penetrates a deposition hole or tunnel but not a canister it may, e.g. if water is circulated, impact the safety functions of the buffer or backfill in addition to provide a pathway for radionuclides. If the borehole does not penetrate any of the repository excavations, 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 capability of the geosphere to provide favourable hydrological, transport and chemical conditions, at least if the borehole intersects water-conducting fractures that are in contact with the repository.

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 utilised 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 capability of the geosphere 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 capability of the geosphere 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 judged 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 Forsmark and Laxemar sites consists of commonly occurring crystalline rocks. 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 utilised.

Impact on the repository and its functions

The capability of the geosphere to provide favourable hydrological and transport conditions may be affected. Since rock surfaces would become 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 judged 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, sealing 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 the impact of 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 complex-forming 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 adsorb radionuclides. Surfactants can help to stabilise 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 judged to be a suitable place to dispose of it. If this method is chosen for disposal 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 have been investigated. If the investigated site is located close to the deep repository, it is likely that the repository will be discovered and recognised 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, these 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 the waste is injected, it 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. Technologies to inject radioactive waste exist and have been employed in the US and in the former Soviet Union. Boreholes are drilled to a suitable depth. The waste is injected directly into permeable layers in the bedrock. It is also possible to increase the rock permeability 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, the capability of the geosphere to provide chemically favourable conditions may be affected, depending on the properties of the injected substance. The capability of the rock to provide favourable hydrological and transport conditions may also 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 sterilised 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 released from the spent fuel repository 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 for this analysis 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, organised 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 FHA-related FEPs in the NEA FEP database, both for SR-Can and for SR-Site; see further the SR-Site FEP report /SKB 2010a/.

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 that we do not yet know about /Popper 1957/. 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 techno-productive 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 definitely 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 and it should be recognised that even in this time span the future of man and society is essentially 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 organised 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 organise 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 summarised 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 economic, democratic values, symbolic values, e.g. for or against nuclear power, and resource utilisation, 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 polarised or evenly distributed,
- intent – benevolent or malicious, self- or public interest,
- motive – e.g. curiosity, exploration, utilisation 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 utilised 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 utilisation 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.

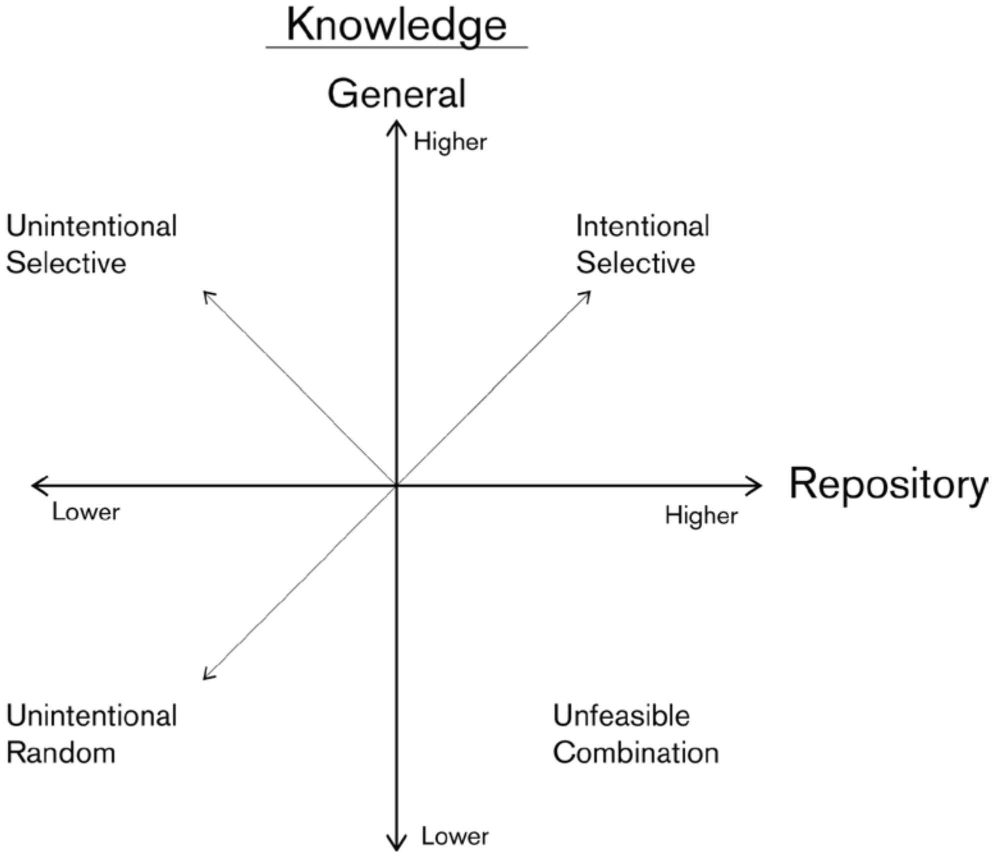


Figure 5-1. *Changes in knowledge and its relation to intent and motive of FHA at the repository site. The origin represents the current situation and the arrows indicate how the likely intent and motive of FHA would develop given the illustrated development of knowledge.*

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 5.3.

In a first phase of their work, the working group at Frösunda 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 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 dependent – they 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 that the variable can express.

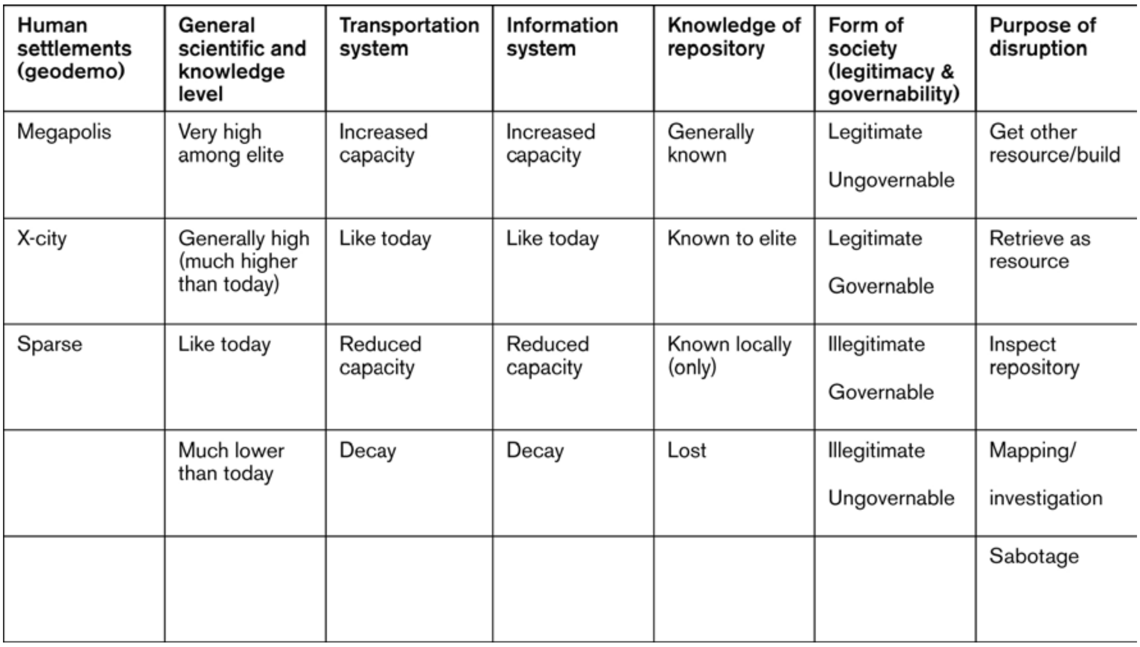
- **Human settlement pattern:** Geodemographic pattern at or near the repository location.
    - Megalopolis – Most people live in very large "modern" cities (e.g. New York City, Tokyo, Los Angeles).
    - X-city – most people live in cities and towns of various sizes[2] (roughly like Sweden today).
    - Sparse – Human settlements are spread out over a large area. "Sparse modern" (such as Iceland, Canada today) or "sparse old-fashioned" (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.

---

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

- **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 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.
  - 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.



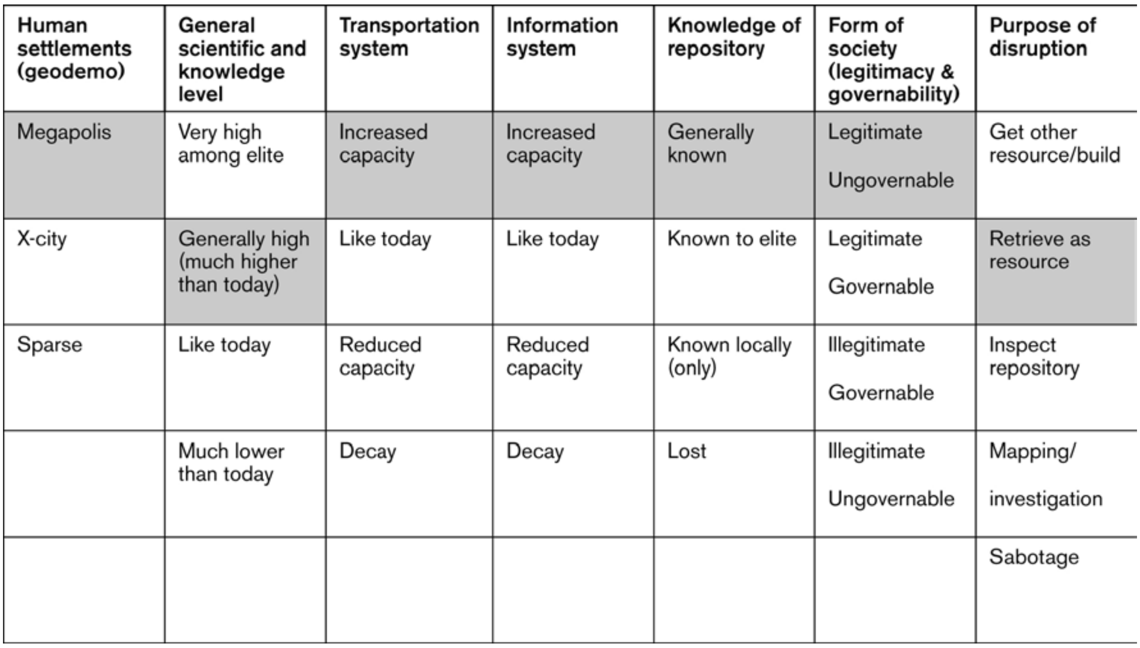
Human settlements (geodemo)	General scientific and knowledge level	Transportation system	Information system	Knowledge of repository	Form of society (legitimacy & governability)	Purpose of disruption
Megapolis	Very high among elite	Increased capacity	Increased capacity	Generally known	Legitimate Ungovernable	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.*

5.3 Analysis and societal scenarios

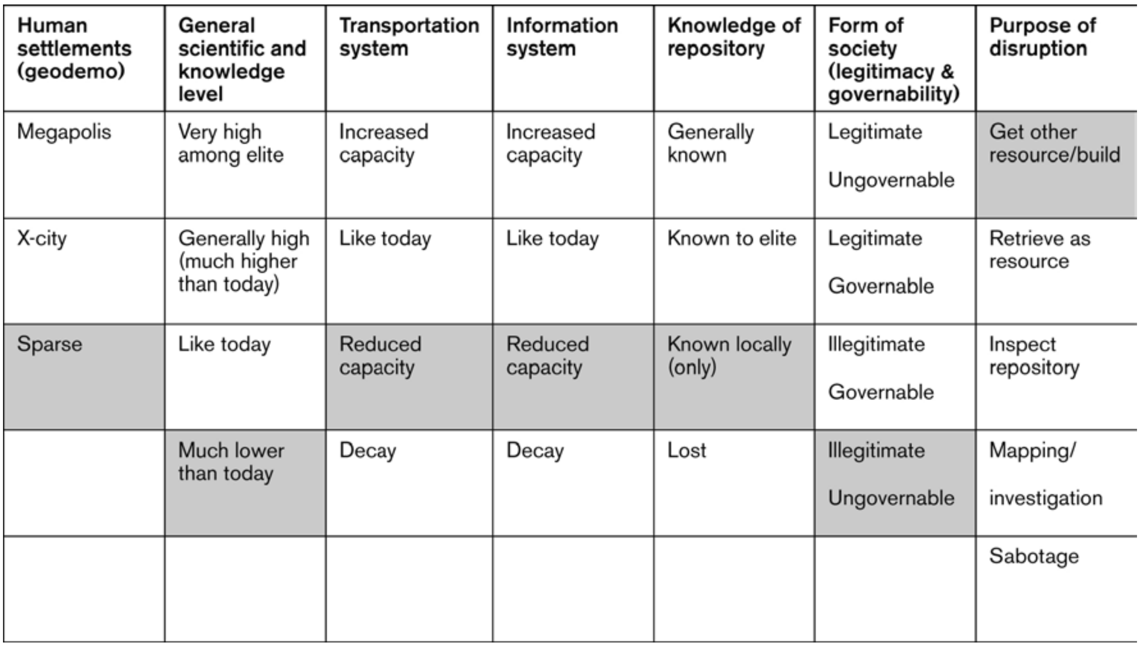
5.3.1 Analysis

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 5-3. *A framework scenario that shows a plausible 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 for, and explanations of, 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 morphological field then obtained the appearance shown in Figure 5-5.

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 (Figure 5-6) 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 (Figure 5-7) 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 that 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.

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.*

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".

The recovery

Recovery (Figure 5-8) 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 5-8.__ The framework scenario "The recovery".

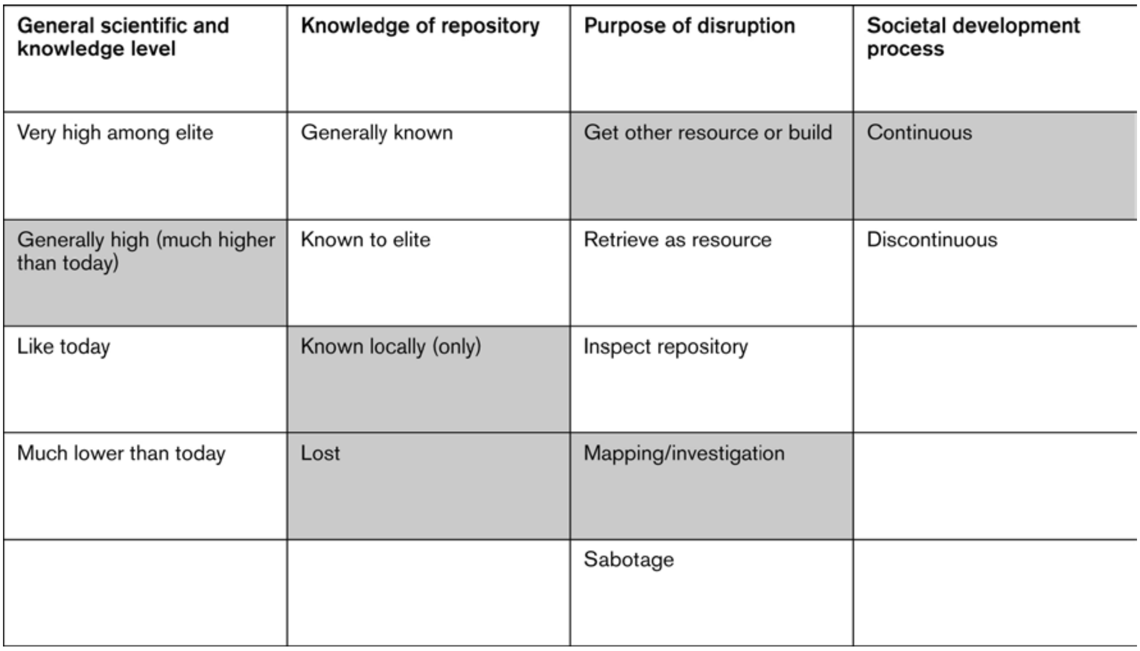
Selective forgetfulness

Selective forgetfulness (Figure 5-9) 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.

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 in which 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.



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”.

6 Illustrative cases of future human actions

The aim of this chapter is to illustrate future human action cases. This is required by the regulations to be a part of the safety assessment SR-Site. All analyses of consequences are reported here and are only briefly summarised in the main report of SR-Site. Selection of FHA-cases is discussed in general in sections 6.1 and 6.2.

Prior to SR-Site, the following three FHA-cases were presented and assessed in SR-Can /SKB 2006a/.

- Canister penetrated by drilling at the earliest 300 years after closure and sealing of the repository, including calculation of dose to a family using the borehole as a well in addition to being exposed to external radiation from the drill cuttings left on the ground at the borehole.
- Underground facility near the repository comprising of a tunnel driven above the repository at 50 metres depth, again not earlier than 300 years after closure and sealing.
- A mine at Forsmark, southwest of the selected repository site, outside the tectonic lens associated with the site and into an area containing an iron oxide mineralisation.

In their joint review of SR-Can the authorities SKI and SSI explain the intention with their requirement associated with human intrusion to overview the conceivable consequences /Dverstorp and Strömberg 2008/. To this end examples are needed such as activities that can indirectly lead to deterioration in the repository's protective capacity, damage caused to the barriers in connection to human activity, injuries to people who intrude into the repository and the consequences of an abandoned but not sealed repository.

The first case did not regard exposure of the drillers, nor any consequences of the initial damage to the rest of the repository. In response to the comments made by the authorities in their review, this case has been further evaluated and presented in Section 6.3.

The second and third case were found to be of little or no consequence for the repository. However, the authorities expert group for review of safety assessment methodology in SR-Can commented that supporting arguments were lacking for the claim that rock chambers, tunnels and mining do not affect the repository /Dverstorp and Strömberg 2008, Annex 2/. These two cases are therefore further addressed in the following sections 6.4 and 6.5.

According to the regulations, it is also necessary to define and analyse a case that illustrates the consequences of an unsealed repository /SKI 2002/. This was not done in SR-Can, but in SR-Site the case of an unsealed, or rather "a not completely sealed repository", has been selected and analysed, see Section 6.6. The name of the case is referring to the fact that deposition tunnels are filled successively, and sealed as soon as they have been filled. Leaving in the middle of such an operation is considered unlikely. It is more plausible that the operation stops and the repository is abandoned after the deposition tunnels have been sealed but the rest of the repository is still open.

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 /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 coincides 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. An application of a combination of ongoing current practice with unintentional actions would lead to a conclusion that inadvertent human actions yielding radiological consequences will not occur. Current activities at the Forsmark site will not impact on repository safety.

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 Choice of illustrative cases

6.2.1 Sealed repository

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 it 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 containment or the function indicators for containment 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 containment has been compromised and there are leaking canisters in the repository.

The repository will be situated at a minimum of 400 metres depth in the rock, and the suggested repository depth is below 450 m at Forsmark. One reason for this is the wish to locate the repository in an environment where the containment 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 containment of the spent 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 judged 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 containment of the spent fuel. 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 containment 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. However, sub-surface testing of nuclear bombs (M6) close to the repository may violate the containment 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. Since measurements are carried out in connections with the tests, it is plausible that if a detectable leakage from the repository exists, it would be distinguished from the releases from the bomb and 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 containment of the spent fuel if they affect the capability of the geosphere to provide favourable hydrological or chemical conditions. Such actions would have to be performed directly above or very close to the 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. Therefore, if present day technology is applied, all these cases involve drilling in the rock.

Large rock facilities adjacent to the repository are judged to be out of the question in a short time perspective, i.e. within a few hundred years, for several reasons. For example, the 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 site, 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 Forsmark (the SFR facility, a repository for low- and intermediate level radioactive waste). In the far future, the potential ore resources to the southwest 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 containment, 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 judged 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. Therefore, 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 been selected as representative for scenarios related to a sealed repository, and which should be further described and analysed.

6.2.2 Unsealed or incompletely sealed repository

According to regulations, it is also necessary to define and analyse a case that illustrates the consequences of an unsealed repository /SKI 2002/. Since the repository is gradually excavated and operated, the case selected for analysis represents an incompletely sealed repository rather than an unsealed repository. The strategy for deposition of canisters implies that deposition tunnels are successively filled with canisters and then backfilled and sealed as soon as they are filled. Abandoning the repository in the middle of this process is judged as rather unlikely because this would mean that canisters are left at the surface where they would constitute a larger risk than if emplaced in the repository. It is judged more plausible that the repository is abandoned when all canisters are deposited and all deposition tunnels backfilled and sealed, but all other repository volumes are still open due to, for example, political decisions not to seal the repository completely. Therefore, this is the basic assumption in the case selected as representative for scenarios related to an unsealed or incompletely sealed repository.

6.3 Assessment of the drilling case

6.3.1 Introduction and specification of the case analysed

Only drilling done without knowledge of the location and purpose of the repository is considered. Various countermeasures to reduce the likelihood of inadvertent intrusion into the repository have been discussed /NEA 1995a, Eng et al. 1996/. When the repository is sealed the countermeasures then judged to be most efficient will be implemented. Examples of such countermeasures are conservation of information in archives, marking the site and various types of institutional control, for example physical surveillance, ownership restrictions and restrictions on land use. All these countermeasures are assumed to have lost their preventive and warning effect at the time for the drilling.

As discussed in Chapter 5, it is hard to imagine a societal evolution resulting in the loss of knowledge of the repository, its purpose and content in combination with preservation or development of knowledge, technology and society. It is likely that a society having the technical capability to drill to great depth also has the knowledge to analyse their findings and possibly will act to prevent harmful effects on man and the environment. In the drilling scenario, it is assumed that technology to drill to great depth is available, that the knowledge of the location and purpose of the repository is lost, that the intruders are incapable of analysing and understanding what they have found and that no societal regulations on drilling exist. It is assumed that an evolution rendering this situation will require some time. Countermeasures to prevent inadvertent intrusion are generally assumed to be preserved for between 100 and 500 years, whereas physical markers may be effective on a longer time perspective of up to a couple of thousand years /NEA 1995a, Wilmot et al. 1999/. A KBS-3 repository is a large industrial establishment that will be under operation for several decades and this type of facility has been debated, investigated and analysed since the first nuclear power plants commenced operation in Sweden. It is plausible that it will take some time before the knowledge about the repository is lost and also for society and land owners to give up the control of activities such as drilling at the repository site. Based on this, it is assumed that the drilling will take place 300 years or longer after repository closure.

The technical practise is assumed to be similar to that at present. Today, drilling is done to sink wells, for the extraction of heat from the ground, and for exploratory purposes. Rock wells are normally drilled to a depth of between 50 and 100 metres, but occasionally wells are drilled down to 130–150 metres. Deeper wells are more uncommon. The reason is that it is expensive to drill and the probability of finding potable water in sufficient quantity declines with depth. For extracting heat, deeper drilling may occur. Even if 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, drilling to great depth is generally done for exploratory purposes, most often prospecting. It is, therefore, assumed that drilling through the repository is done for exploratory purposes.

Diamond (core) drilling is normally employed for exploratory drilling. The drill core is retrieved, placed in boxes and inspected by a geologist. Selected samples may be analysed more thoroughly. The cuttings (the pulverised rock mixed with the drill's cooling water) are normally removed with water, which also cools the drill. The water with cuttings is usually spread on the ground around the borehole. When the drilling is finished, the cores are sent to core mapping and the borehole is abandoned. If the hole has passed a zone with high water flow, so that a great deal of water is brought up to the surface, the borehole may be backfilled. This is generally only done if the flow entails a problem for local residents.

The direction of the borehole varies depending on the purpose and what is known about the rock volume to be investigated. In general the drill is inclined; the angle with the ground plane is usually 60–85°. If there are no known obstacles or underground facilities, the drillers always try to continue the drilling even if they run into problems. If the drill reaches the buffer and the canister, these may very well be penetrated and the drilling continued and not stopped until the drill core is inspected, or the agreed depth is reached. If penetration of the backfilled deposition tunnel occurs, 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 is frequently grouted and the drilling continued through the concrete.

It is assumed that the purpose of the drilling is to reach great depth and that the drill rig therefore is placed at a low point in the terrain. The drilling angle is assumed to be 85° and the cuttings are assumed to be spread on the ground. When the backfilled tunnel is reached the borehole is assumed to be grouted and the drilling continued. The buffer is assumed to be grouted as well, the drilling continued and the canister penetrated. When the drill core containing canister material and spent nuclear fuel is brought to the surface the anomalous situation is taken to be recognised and the drilling is stopped.

Since the assessment should not only consider the impact to the intruder, but also assess how the safety functions of the repository may be impaired, the following additional assumptions are made: The site and the borehole are abandoned without further measures. About a month later, a family moves to the site and operates a domestic production farm there. The abandoned borehole is used as a well by the family. The dose to the drilling personnel from external exposure from radionuclides in the cuttings and in the spent fuel in the cores and the annual effective doses to the family are assessed. In addition, the consequences for the repository, including long-term effects of the initial damage on the rest of the repository, are estimated.

6.3.2 Assessment of the dose consequences of unintentionally penetrating a canister when drilling

Concepts, assumptions and data

It is assumed that one canister is penetrated by core drilling and that this takes place at the earliest 300 years after repository closure. The borehole above the penetrated canister is assumed to be grouted and the capability of the buffer to prevent advective transport, self seal and prevent colloid transport are lost in the grouted area. Some buffer and backfill material is lost, but excluding the grouted parts, both backfill and buffer are assumed to retain their safety functions. This assumption is justified by the relatively small diameter of the borehole compared to the volume of the buffer and backfill. The water containing the cuttings from the drilling is brought to the surface and spread on the ground on a circular area. The drilling personnel receives dose from radionuclides in the cuttings and drilling water.

The fuel is contained as fuel rods in fuel assemblies in the cast iron insert in the copper canisters. Assumptions regarding the amount of spent fuel brought to the surface depend on the geometry and arrangement of the fuel rods in the canister and the dimension of the penetrating borehole. The drilling angle through the rock is assumed to be 85°, but in the analysis it is simplistically assumed that the drilling through the canister occurs along the axis of the canister. The borehole diameter is assumed to be 0.056 m, which is the size of the core-drilled investigation boreholes at Forsmark that produce rock cores with a diameter of 0.051 m. With these assumptions and considering the geometry and arrangement of the fuel rods in the canister, the portion of the fuel in the canister that is brought to the surface is estimated to be on the order of 2 to 3%. Additional information on how these values are obtained is provided in section B.1 in Appendix B. For calculation of the dose consequences it is assumed that 3% of the fuel in a penetrated canister is brought to the surface, mainly as cuttings in the drilling water and as pieces of fuel rods, but possibly also as a few undamaged fuel rods.

Radionuclides in the spent fuel are contained in the uranium dioxide matrix, but also in metal parts of the fuel. In addition, the spent fuel contains fission gases that are rapidly released. In the analysis it is assumed that some radionuclides in the spent fuel in the penetrated canister are, to various degree, immediately accessible and dissolved in the drilling water during drilling, the instantaneous release fraction (IRF). The radionuclide inventory in the canister 300 years after repository closure used in the analyses are given in Table 6-1. The inventory is derived for an average canister and reported in the SR-Site radionuclide transport report /SKB 2010c/ and is based on the inventory justified and provided in the SR-Site data report /SKB 2010d/. The distribution of the inventory between the instantaneous release fraction, the metal parts and the uranium matrix is also reported in the SR-Site data report /SKB 2010d/ and for the calculations here, the median values for the instantaneous release fraction and the fraction in the metal parts are used (Table 6-1).

Radionuclides in the cuttings and fuel pieces, as well as the instant release fraction of the inventory in the canister that are brought to the surface with the drilling are spread on the ground. It is assumed that this occurs over a circular area and that the radius of the contaminated area is 3 m and that the thickness of the contaminated soil layer is 0.1 m. The amounts of radionuclides in cuttings and drilling water as well as the resulting concentration in the soil surrounding the borehole are provided in Table 6-1. These concentrations are based on the assumption that all fuel brought to the surface remain at the site. If some of the fuel rods are undamaged and brought up as a core from the drilling and removed from the site, the concentrations in the contaminated area would be lower.

Table 6-1. Radionuclide inventory in an average canister 300 years after repository closure /SKB 2010c, Appendix E, corrected inventory/ and the fraction (median values) of the inventory in various fuel parts /SKB 2010d, Section 3.2/ together with the estimated amounts of radionuclides brought to the surface by drilling water and the resulting concentration in the soil surrounding the borehole.

Radionuclide	Inventory in canister (Bq)	Fraction of inventory in			Inventory brought to surface (Bq)	Concentration in soil (Bq/m^3)
		IRF	Metal	UO$_2$ matrix		
Ac-227	$9.11\cdot10^{6}$	0	0	1.00	$2.73\cdot10^{5}$	$9.66\cdot10^{4}$
Ag-108m	$2.04\cdot10^{12}$	1.00	0	0	$2.04\cdot10^{12}$	$7.22\cdot10^{11}$
Am-241	$2.01\cdot10^{14}$	0	0	1.00	$6.04\cdot10^{12}$	$2.14\cdot10^{12}$
Am-242m	$1.44\cdot10^{11}$	0	0	1.00	$4.32\cdot10^{9}$	$1.53\cdot10^{9}$
Am-243	$2.21\cdot10^{12}$	0	0	1.00	$6.64\cdot10^{10}$	$2.35\cdot10^{10}$
C-14	$5.87\cdot10^{10}$	0.092	0.644	0.264	$7.00\cdot10^{9}$	$2.48\cdot10^{9}$
Cd-113m	$8.38\cdot10^{4}$	1.00	0	0	$8.38\cdot10^{4}$	$2.96\cdot10^{4}$
Cl-36	$3.86\cdot10^{8}$	0.086	0.015	0.899	$4.38\cdot10^{7}$	$1.55\cdot10^{7}$
Cm-245	$3.49\cdot10^{10}$	0	0	1.00	$1.05\cdot10^{9}$	$3.70\cdot10^{8}$
Cm-246	$6.46\cdot10^{9}$	0	0	1.00	$1.94\cdot10^{8}$	$6.85\cdot10^{7}$
Cs-135	$3.87\cdot10^{10}$	0.029	0	0.971	$2.24\cdot10^{9}$	$7.92\cdot10^{8}$
Cs-137	$2.13\cdot10^{12}$	0.029	0	0.971	$1.23\cdot10^{11}$	$4.35\cdot10^{10}$
Eu-152	$4.68\cdot10^{3}$	0	0	1.00	140	49.7
H-3	$7.01\cdot10^{4}$	1.00	0	0	$7.01\cdot10^{4}$	$2.48\cdot10^{4}$
Ho-166m	$6.21\cdot10^{9}$	0	0	1.00	$1.86\cdot10^{8}$	$6.59\cdot10^{7}$
I-129	$2.28\cdot10^{9}$	0.029	0	0.971	$1.32\cdot10^{8}$	$4.66\cdot10^{7}$
Mo-93	$4.41\cdot10^{8}$	0.012	0.810	0.180	$1.83\cdot10^{7}$	$6.48\cdot10^{6}$
Nb-93m	$3.45\cdot10^{7}$	0.017	0.983	0.0001	$1.61\cdot10^{6}$	$5.68\cdot10^{5}$
Nb-94	$1.51\cdot10^{11}$	0.018	0.982	0	$7.11\cdot10^{9}$	$2.51\cdot10^{9}$
Ni-59	$2.81\cdot10^{11}$	0.012	0.964	0.024	$1.16\cdot10^{10}$	$4.10\cdot10^{9}$
Ni-63	$3.19\cdot10^{12}$	0.012	0.965	0.023	$1.31\cdot10^{11}$	$4.65\cdot10^{10}$
Np-237	$5.68\cdot10^{10}$	0	0	1.00	$1.71\cdot10^{9}$	$6.03\cdot10^{8}$
Pa-231	$9.82\cdot10^{6}$	0	0	1.00	$2.95\cdot10^{5}$	$1.04\cdot10^{5}$
Pb-210	$2.63\cdot10^{7}$	0	0	1.00	$7.90\cdot10^{5}$	$2.79\cdot10^{5}$
Pd-107	$9.73\cdot10^{9}$	0.002	0	0.998	$3.11\cdot10^{8}$	$1.10\cdot10^{8}$
Pu-238	$1.70\cdot10^{13}$	0	0	1.00	$5.10\cdot10^{11}$	$1.80\cdot10^{11}$
Pu-239	$2.29\cdot10^{13}$	0	0	1.00	$6.88\cdot10^{11}$	$2.43\cdot10^{11}$
Pu-240	$4.04\cdot10^{13}$	0	0	1.00	$1.21\cdot10^{12}$	$4.28\cdot10^{11}$
Pu-242	$1.85\cdot10^{11}$	0	0	1.00	$5.55\cdot10^{9}$	$1.96\cdot10^{9}$
Ra-226	$3.19\cdot10^{7}$	0	0	1.00	$9.56\cdot10^{5}$	$3.38\cdot10^{5}$
Se-79	$1.59\cdot10^{9}$	0.0042	0.0001	0.9957	$5.43\cdot10^{7}$	$1.92\cdot10^{7}$
Sm-151	$1.88\cdot10^{12}$	0	0	1.00	$5.63\cdot10^{10}$	$1.99\cdot10^{10}$
Sn-121m	$2.83\cdot10^{10}$	0.0002	0.5152	0.4846	$8.54\cdot10^{8}$	$3.02\cdot10^{8}$
Sn-126	$4.48\cdot10^{10}$	0.0003	0	0.9997	$1.36\cdot10^{9}$	$4.80\cdot10^{8}$
Sr-90	$9.95\cdot10^{11}$	0.003	0	0.997	$3.23\cdot10^{10}$	$1.14\cdot10^{10}$
Tc-99	$1.12\cdot10^{12}$	0.0020	0.0001	0.9979	$3.58\cdot10^{10}$	$1.27\cdot10^{10}$
Th-229	$1.12\cdot10^{6}$	0	0	1.00	$3.35\cdot10^{4}$	$1.18\cdot10^{4}$
Th-230	$4.73\cdot10^{8}$	0	0	1.00	$1.42\cdot10^{7}$	$5.02\cdot10^{6}$
Th-232	400	0	0	1.00	12	4.24
U-233	$7.04\cdot10^{7}$	0	0.25	0.75	$2.11\cdot10^{6}$	$7.47\cdot10^{5}$
U-234	$1.70\cdot10^{11}$	0	0	1.00	$5.11\cdot10^{9}$	$1.81\cdot10^{9}$
U-235	$1.09\cdot10^{9}$	0	0	1.00	$3.27\cdot10^{7}$	$1.16\cdot10^{7}$
U-236	$2.25\cdot10^{10}$	0	0	1.00	$6.75\cdot10^{8}$	$2.39\cdot10^{8}$
U-238	$2.13\cdot10^{10}$	0	0	1.00	$6.40\cdot10^{8}$	$2.26\cdot10^{8}$
Zr-93	$1.70\cdot10^{11}$	0.00001	0.12518	0.87481	$5.11\cdot10^{9}$	$1.81\cdot10^{9}$

In this drilling case it is further assumed that a family settles on the site one month after the site is abandoned by the drillers. The grouted borehole has left an open pipe from the penetrated canister to the surface and the family uses the borehole as a well. In addition, the contaminated soil is used for cultivation purposes. The family receives dose from radionuclides in the borehole water as well as from radionuclides in agricultural products and air, the latter originating from radionuclides in the contaminated soil.

The release rate of radionuclides to the borehole water is dependent on the radionuclide release rate from the uranium matrix and from the metal components. These entities are in turn dependent on the fuel alteration rate and the corrosion rate of the metal components, respectively. However, elemental solubility limits may govern the release of some radionuclides, depending on the magnitude of the water flow in the deposition hole containing the penetrated canister. Results from the hydrogeological modelling /Joyce et al. 2010/ are used to estimate the magnitude of the water flow in the deposition hole containing the penetrated canister. This is further described in section B.2 in Appendix B. Based on the results obtained it is assumed that the water flow in the deposition hole with the penetrated canister is 0.1 m^3/year. Since the flow if water is from the rock to the borehole and the buffer is assumed to seal the borehole damage, reducing conditions will prevail in the penetrated canister. The fuel alteration rate assumed is 10^{-7} per year, which is the median value for reducing conditions as provided in the SR-Site data report /SKB 2010d, Section 3.3/. Furthermore, the median value for corrosion of the metal parts of the fuel of 10^{-3} per year, as provided in the SR-Site data report /SKB 2010d/, is assumed. The calculated release rates of radionuclides to the borehole water and the corresponding concentrations in the water in the canister are given in Table 6-3. The elemental solubility limits used are derived for groundwater chemical conditions representative for temperate climate conditions in the time period 2000 to 3000 AD, derived as reported in Appendix F to the SR-Site radionuclide transport report /SKB 2010c/. Also here the median values of the solubility limits are used and these values are provided in Table 6-2.

Table 6-2. Elemental solubility limits used in the calculations. Median values representative of groundwater chemical conditions between 2000 and 3000 AD during the temperate period.

Element	Solubility limit (mol/m³)	Element	Solubility limit (mol/m³)
Ag	$1.24\cdot10^{-2}$	Pu	$5.53\cdot10^{-3}$
Am	$1.84\cdot10^{-3}$	Ra	$5.96\cdot10^{-4}$
Cm	$2.29\cdot10^{-3}$	Se	$6.65\cdot10^{-6}$
Ho	$3.57\cdot10^{-3}$	Sm	$1.04\cdot10^{-4}$
Nb	$4.95\cdot10^{-2}$	Sn	$9.13\cdot10^{-5}$
Ni	$2.93\cdot10^{-1}$	Sr	2.63
Np	$1.10\cdot10^{-6}$	Tc	$3.86\cdot10^{-6}$
Pa	$3.29\cdot10^{-4}$	Th	$3.50\cdot10^{-6}$
Pb	$1.52\cdot10^{-3}$	U	$9.82\cdot10^{-7}$
Pd	$3.95\cdot10^{-6}$	Zr	$1.76\cdot10^{-5}$

Table 6-3. Calculated release rates of radionuclides from the fuel and corresponding concentrations in the water in the canister 300 years after repository closure.

Radionuclide	Concentration in canister water		Release rate from fuel	
	(mol/m^3)	(Bq/m^3)	(mol/year)	(Bq/year)
Ac-227	$1.45\cdot10^{-14}$	8.83	$1.45\cdot10^{-15}$	0.883
Ag-108m	0	0	0	0
Am-241	$6.38\cdot10^{-6}$	$1.95\cdot10^{8}$	$6.38\cdot10^{-7}$	$1.95\cdot10^{7}$
Am-242m	$1.49\cdot10^{-9}$	$1.40\cdot10^{5}$	$1.49\cdot10^{-10}$	$1.40\cdot10^{4}$
Am-243	$1.19\cdot10^{-6}$	$2.15\cdot10^{6}$	$1.19\cdot10^{-7}$	$2.15\cdot10^{5}$
C-14	$1.59\cdot10^{-4}$	$3.67\cdot10^{8}$	$1.59\cdot10^{-5}$	$3.67\cdot10^{7}$
Cd-113m	0	0	0	0
Cl-36	$1.30\cdot10^{-6}$	$5.70\cdot10^{4}$	$1.30\cdot10^{-7}$	$5.70\cdot10^{3}$
Cm-245	$2.17\cdot10^{-8}$	$3.38\cdot10^{4}$	$2.17\cdot10^{-9}$	$3.38\cdot10^{3}$
Cm-246	$2.24\cdot10^{-9}$	$6.26\cdot10^{3}$	$2.24\cdot10^{-10}$	626
Cs-135	$6.34\cdot10^{-6}$	$3.65\cdot10^{4}$	$6.34\cdot10^{-7}$	$3.65\cdot10^{3}$
Cs-137	$4.55\cdot10^{-9}$	$2.00\cdot10^{6}$	$4.55\cdot10^{-10}$	$2.00\cdot10^{5}$
Eu-152	$4.64\cdot10^{-18}$	$4.54\cdot10^{-3}$	$4.64\cdot10^{-19}$	$4.54\cdot10^{-4}$
H-3	0	0	0	0
Ho-166m	$5.46\cdot10^{-10}$	$6.02\cdot10^{3}$	$5.46\cdot10^{-11}$	602
I-129	$2.54\cdot10^{-6}$	$2.14\cdot10^{3}$	$2.54\cdot10^{-7}$	214
Mo-93	$1.05\cdot10^{-6}$	$3.46\cdot10^{6}$	$1.05\cdot10^{-7}$	$3.46\cdot10^{5}$
Nb-93m	$4.01\cdot10^{-10}$	$3.29\cdot10^{5}$	$4.01\cdot10^{-11}$	$3.29\cdot10^{4}$
Nb-94	$2.20\cdot10^{-3}$	$1.44\cdot10^{9}$	$2.20\cdot10^{-4}$	$1.44\cdot10^{8}$
Ni-59	$1.51\cdot10^{-2}$	$2.63\cdot10^{9}$	$1.51\cdot10^{-3}$	$2.63\cdot10^{8}$
Ni-63	$2.26\cdot10^{-4}$	$2.99\cdot10^{10}$	$2.26\cdot10^{-5}$	$2.99\cdot10^{9}$
Np-237 *	$1.10\cdot10^{-6}$	$6.77\cdot10^{3}$	$1.10\cdot10^{-7}$	677
Pa-231	$2.36\cdot10^{-11}$	9.53	$2.36\cdot10^{-12}$	0.953
Pb-210	$4.30\cdot10^{-14}$	25.5	$4.30\cdot10^{-15}$	2.55
Pd-107	$4.63\cdot10^{-6}$	$9.42\cdot10^{3}$	$4.63\cdot10^{-7}$	942
Pu-238	$1.09\cdot10^{-7}$	$1.65\cdot10^{7}$	$1.09\cdot10^{-8}$	$1.65\cdot10^{6}$
Pu-239	$4.05\cdot10^{-5}$	$2.22\cdot10^{7}$	$4.05\cdot10^{-6}$	$2.22\cdot10^{6}$
Pu-240	$1.94\cdot10^{-5}$	$3.92\cdot10^{7}$	$1.94\cdot10^{-6}$	$3.92\cdot10^{6}$
Pu-242	$5.06\cdot10^{-6}$	$1.79\cdot10^{5}$	$5.06\cdot10^{-7}$	$1.79\cdot10^{4}$
Ra-226	$3.74\cdot10^{-12}$	30.9	$3.74\cdot10^{-13}$	3.09
Se-79	$3.01\cdot10^{-7}$	$3.53\cdot10^{3}$	$3.01\cdot10^{-8}$	353
Sm-151	$1.24\cdot10^{-8}$	$1.82\cdot10^{6}$	$1.24\cdot10^{-9}$	$1.82\cdot10^{5}$
Sn-121m	$5.88\cdot10^{-7}$	$1.41\cdot10^{8}$	$5.88\cdot10^{-8}$	$1.41\cdot10^{7}$
Sn-126	$3.28\cdot10^{-7}$	$4.34\cdot10^{4}$	$3.28\cdot10^{-8}$	$4.34\cdot10^{3}$
Sr-90	$2.09\cdot10^{-9}$	$9.63\cdot10^{5}$	$2.09\cdot10^{-10}$	$9.63\cdot10^{4}$
Tc-99 *	$3.86\cdot10^{-6}$	$2.42\cdot10^{5}$	$3.86\cdot10^{-7}$	$2.42\cdot10^{4}$
Th-229	$6.00\cdot10^{-13}$	1.08	$6.00\cdot10^{-14}$	0.108
Th-230	$2.61\cdot10^{-9}$	459	$2.61\cdot10^{-10}$	45.9
Th-232	$4.12\cdot10^{-10}$	$3.88\cdot10^{-4}$	$4.12\cdot10^{-11}$	$3.88\cdot10^{-5}$
U-233 **	$1.14\cdot10^{-13}$	$9.47\cdot10^{-3}$	$1.14\cdot10^{-14}$	$9.47\cdot10^{-4}$
U-234 **	$4.25\cdot10^{-10}$	22.9	$4.25\cdot10^{-11}$	2.29
U-235 **	$7.80\cdot10^{-9}$	0.147	$7.80\cdot10^{-10}$	$1.47\cdot10^{-2}$
U-236 **	$5.36\cdot10^{-9}$	3.03	$5.36\cdot10^{-10}$	0.303
U-238 **	$9.69\cdot10^{-7}$	2.87	$9.69\cdot10^{-8}$	0.287
Zr-93 *	$1.76\cdot10^{-5}$	$1.53\cdot10^{5}$	$1.76\cdot10^{-6}$	$1.53\cdot10^{4}$

* solubility limited

** solubility limited; concentration and release from fuel set in proportion to the fraction of the isotope in the spent fuel inventory

As indicated in Table 6-3, the elemental solubility limits the release of Np-237, Tc-99, Zr-93 and the uranium isotopes from the spent fuel. The release rate and concentration of the uranium isotopes are estimated by setting their contribution to the solubility concentration proportional to their fraction in the spent fuel inventory.

Dose assessment

Doses to the drilling personnel and to a family that settles on the site have been calculated. The data used in the calculations are compiled in Table 6-4.

The dose to the drilling personnel originates from the radionuclides in cuttings, drilling water and fuel pieces spread on the ground around the borehole. Table 6-5 gives the dose rate that a member of the drilling personnel would be exposed to while working in the highly contaminated area if the drilling takes place 300 years after repository closure. In Figure 6-1, the dose rate as a function of time after repository closure is provided. The total dose rate at 300 years after repository closure is 130 mSv/hour and is totally dominated by exposure to Ag-108m. At c. 5,000 years after repository closure, Nb-94 and Sn-126 become the dominating nuclides.

If the nuclides brought to surface are assumed to remain on the surface for a significant time before infiltrating into the soil, the dose rate to workers would be still higher. A calculation for the initially most dominating radionuclide Ag-108m under such conditions results in a dose rate of 400 mSv/hour for this nuclide only, 300 years after repository closure.

Table 6-4. Data used in the calculation of dose consequences of penetrating a canister when drilling.

Parameter	Value/assumption	Comment/reference
Time of drilling	300 years after closure of the repository or later	
Initial concentration of radionuclides in the soil	Calculated for a radius of the contaminated area of 3 m and a thickness of the contaminated soil layer of 0.1 m.	Table 6-1
Time a member of the family spends in the contaminated area	365 hours	One hour per day every day of the year
Dose conversion factors for contaminated ground	Dose factors for external irradiation, inhalation and ingestion of food cultivated at the site	/Nordén et al. 2010/
Sorption coefficients	Element specific sorption coefficients for soil in the irrigated area	/Nordén et al. 2010/
Area of land used to grow vegetables	102 m^2	Large enough to produce vegetables for 5 persons, assuming a fraction of 2.5% vegetables in diet
Dust concentration in the air	5 10^{-8}kg dry weight/m^3	/Nordén et al. 2010/
Inhalation rate	1 m^3 per hour	/Nordén et al. 2010/
Yearly intake of carbon	110 kg carbon per year	/Nordén et al. 2010/
Yearly intake of water	0.6 m^3/year	/Nordén et al. 2010/
Productivity of vegetables on irrigated land	0.135 kgC per m^2 and year	/Löfgren 2010/
Productivity of root crops on irrigated land	0.127 kgC per m^2 and year	/Löfgren 2010/
Productivity of cereals on irrigated land	0.114 kgC per m^2 and year	/Löfgren 2010/
Density of agricultural soil	323 kg dry weight/m^3	/Löfgren 2010/
Volume of irrigation water used each year	0.15 $m^3/(m^2\ y)$	/Nordén et al. 2010/
Number of irrigation events per year	5	/Nordén et al. 2010/
Runoff	0.186 m/y	/Löfgren 2010/
Well capacity	82,502 m^3/year	/Löfgren 2010/

Table 6-5. Dose rate to drilling personnel from radionuclides brought to the surface 300 years after repository closure.

Radionuclide	Dose rate (Sv/hour)	Radionuclide	Dose rate (Sv/hour)
Ac-227	$8.31\cdot10^{-13}$	Pb-210	$1.06\cdot10^{-11}$
Ag-108m	$1.23\cdot10^{-1}$	Pd-107	$0.00\cdot10^{0}$
Am-241	$1.54\cdot10^{-3}$	Pu-238	$3.97\cdot10^{-7}$
Am-242m	$4.28\cdot10^{-8}$	Pu-239	$1.24\cdot10^{-6}$
Am-243	$5.63\cdot10^{-5}$	Pu-240	$9.42\cdot10^{-7}$
C-14	$5.20\cdot10^{-10}$	Pu-242	$3.73\cdot10^{-9}$
Cd-113m	$3.70\cdot10^{-13}$	Ra-226	$1.89\cdot10^{-10}$
Cl-36	$7.43\cdot10^{-10}$	Se-79	$5.76\cdot10^{-12}$
Cm-245	$2.18\cdot10^{-6}$	Sm-151	$2.59\cdot10^{-10}$
Cm-246	$1.10\cdot10^{-10}$	Sn-121m	$1.14\cdot10^{-8}$
Cs-135	$4.91\cdot10^{-10}$	Sn-126	$1.34\cdot10^{-4}$
Cs-137	$2.83\cdot10^{-3}$	Sr-90	$1.37\cdot10^{-7}$
Eu-152	$6.46\cdot10^{-12}$	Tc-99	$2.66\cdot10^{-8}$
H-3	$0.00\cdot10^{0}$	Th-229	$6.63\cdot10^{-11}$
Ho-166m	$1.25\cdot10^{-5}$	Th-230	$1.05\cdot10^{-10}$
I-129	$8.38\cdot10^{-9}$	Th-232	$3.73\cdot10^{-17}$
Mo-93	$5.18\cdot10^{-11}$	U-233	$1.79\cdot10^{-11}$
Nb-93m	$1.14\cdot10^{-12}$	U-234	$1.19\cdot10^{-8}$
Nb-94	$4.53\cdot10^{-4}$	U-235	$1.50\cdot10^{-7}$
Ni-59	$0.00\cdot10^{0}$	U-236	$8.11\cdot10^{-10}$
Ni-63	$0.00\cdot10^{0}$	U-238	$3.39\cdot10^{-10}$
Np-237	$7.84\cdot10^{-7}$	Zr-93	$0.00\cdot10^{0}$
Pa-231	$3.54\cdot10^{-10}$	Total	$1.28\cdot10^{-1}$

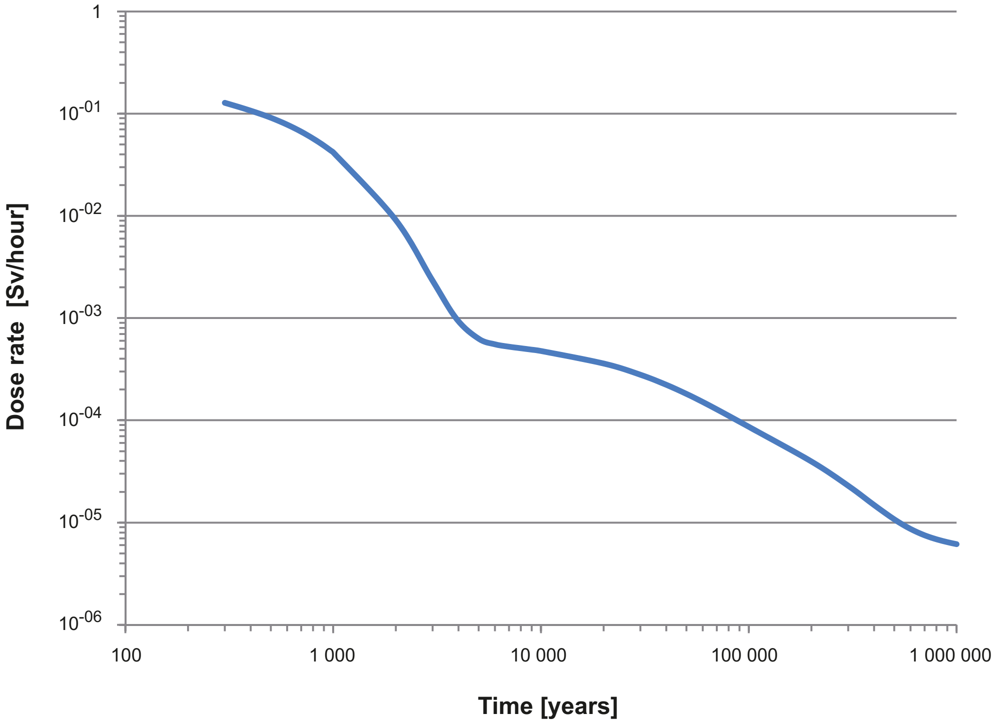


Figure 6-1. Dose rate to drilling personnel working in the contaminated area as a function of time after repository closure that the drilling takes place.

These calculated dose rates are very high. This is primarily a result of the cautious assumption regarding the amount of Ag-108m brought to the surface when drilling. In the spent fuel, Ag-108m is contained in the Ag-In-Cd alloy of the control rods, but is in the calculations assumed to be part of the radionuclides that are instantly released when a canister is penetrated and therefore the entire amount is brought to the surface. In case Ag-108m would not be instantaneously released, 3% instead of 100% of the inventory of Ag-108m would be brought to the surface when drilling. Due to the total dominance of Ag-108m to the dose rate, this would reduce the dose rate to workers to 3% of the value, i.e. the dose rate 300 years after repository closure would be about 4 mSv/hour.

Since an acute dose of 1 Sv is the limit for suffering from radiation sickness some hours to days after exposure, it is clear that the workers would get seriously injured if exposed to the amount of radionuclides assumed to be brought to the surface in this calculation case.

The dose to a family that settles on the site originates from two sources. The abandoned borehole used as a well by the family and the radionuclides in cuttings and spent fuel spread on the ground. The assumptions in the calculations of the dose obtained from using the abandoned borehole as a well are the same as those in the dose calculations for other scenarios analysed in SR-Site /Avila et al. 2010/. It is assumed that the water from the borehole is used for irrigation and as drinking water for the family and for cattle. In the calculation of dose from radionuclides spread on the ground, it is assumed that the family uses the contaminated soil to establish a domestic garden for cultivation of vegetables. This garden is assumed to be large enough to produce vegetables for five persons, which implies that the radionuclides brought to the surface are spread over a larger area. The members of the family are also exposed to external radiation and through inhalation of dust when spending time in the garden.

The calculated annual effective dose from using the abandoned borehole as a well and from the radionuclides spread on the ground are shown in Figure 6-2 and Figure 6-3, respectively. The calculated annual effective dose is that which an adult member of the family would be exposed to during the first year at the site.

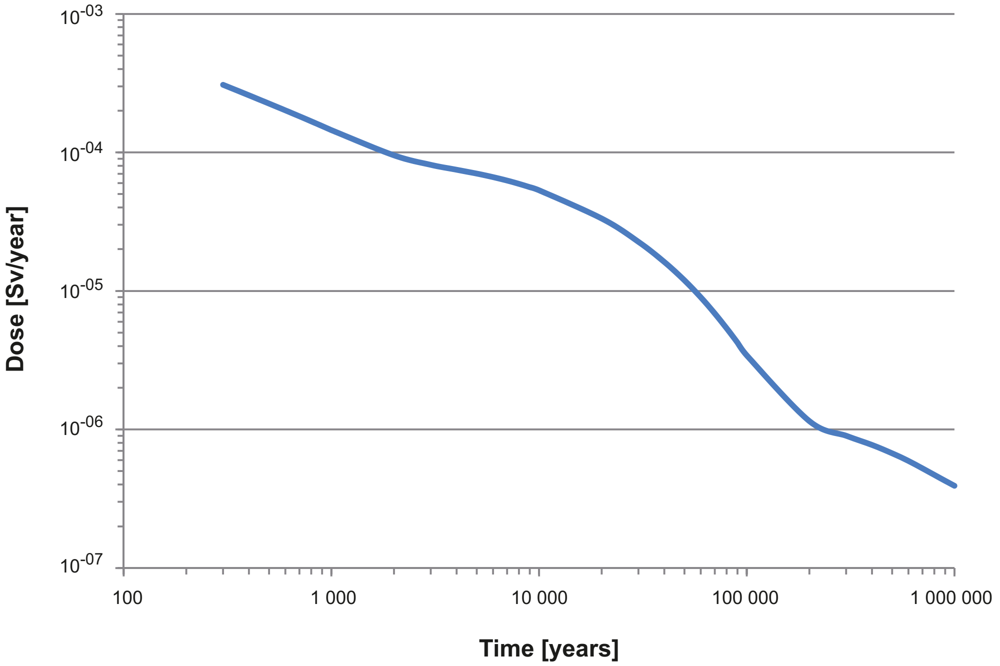


Figure 6-2. *Calculated annual effective doses from using the borehole as a well for drinking water and irrigation at Forsmark. The dose is that which an adult member of the family would be exposed to during the first year at the site and the time is the year after repository closure when drilling takes place and the family settles on the site. This means that the only loss of radionuclides accounted for is that through radioactive decay.*

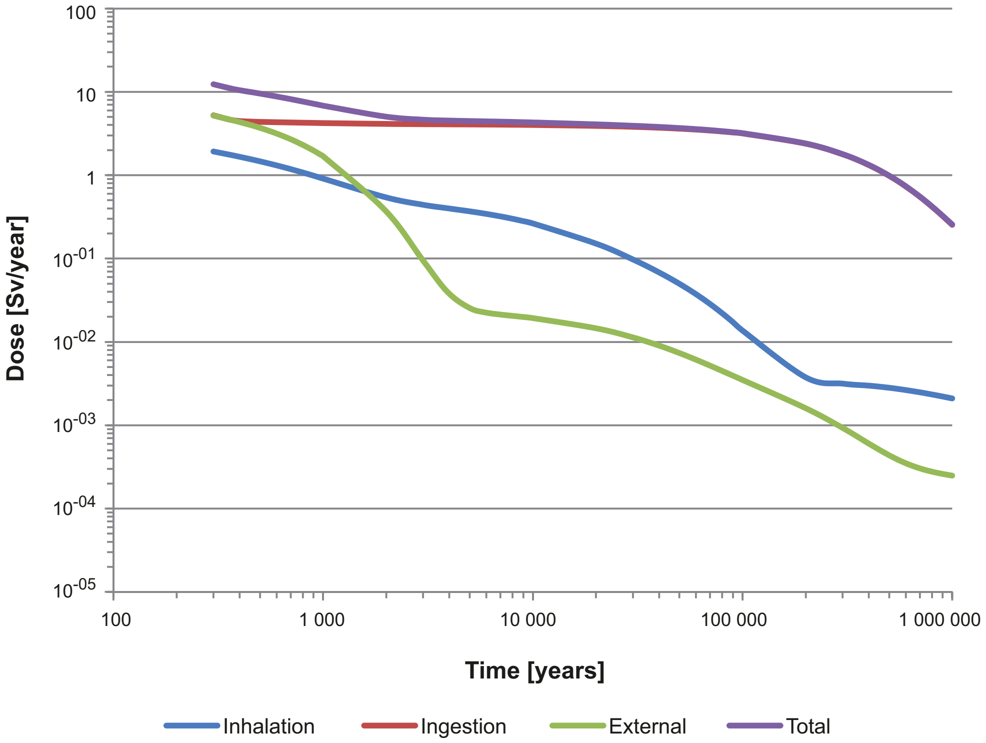


Figure 6-3. *Calculated annual effective doses from exposure to the radionuclides brought to the surface via the use of the contaminated soil for domestic farming and through spending time in the contaminated area. The dose is that which an adult member of the family would be exposed to during the first year at the site and the time is the year after repository closure when drilling takes place and the family settles on the site. This means that the only loss of radionuclides accounted for is that through radioactive decay.*

The total dose from using the borehole as a well 300 years after repository closure is 0.31 mSv/year and is dominated by the contribution from Am-241. This dose is above the regulatory risk limit of 0.014 mSv/year, but below the dose of background radiation, which is at least 1 mSv/year. At 2,000 years after repository closure, the dose is dominated by Pu-240 and if drilling takes place at still later times, Pu-239 and Nb-94 become more significant.

The maximum total annual effective dose from the use of the contaminated soil for agricultural purposes is about 10 Sv/year and this dose is obtained 300 years after repository closure. The dose is dominated by ingestion of vegetables contaminated with Tc-99 and there is also a significant dose contribution due to external radiation from Ag-108m. The calculated annual dose is very high, but it should be noted that there are a number of simplified, cautious assumptions made in the calculations. These are further discussed in Section 6.3.4.

6.3.3 Assessment of the effects on the repository of unintentionally penetrating a canister when drilling

Concepts and results

In the analysed drilling case, it is assumed that the borehole above the penetrated canister is grouted. As long as the grout remains intact, the tunnel backfill in the deposition tunnel and the buffer in the remainder of the deposition holes in the deposition tunnels are not directly affected by the presence of the borehole. With time, it is likely that the grout is degraded and that the buffer and backfill above the penetrated canister expands to fill the empty volume of the borehole in these barriers. Considering the self-healing capacity of the buffer and backfill and the quite large amounts of buffer and backfill materials that can be lost before advective conditions occur /Åkesson et al. 2010, Chapters 6, 11 and Appendix F/ it seems likely that this expansion will re-establish favourable hydraulic and mechanical conditions in the buffer in the deposition hole with the penetrated canister and in the backfill above this deposition hole. However, even if this is not the case, the borehole will not affect the backfill in other parts of the deposition tunnel. This implies that the buffer in other deposition holes in the tunnel also will be unaffected by the borehole.

Initially, the grouted borehole has left an open pipe from the penetrated canister to the surface, which, at least locally, may affect the groundwater flow pattern. The impact of an open borehole on the groundwater flow in the repository and the surrounding rock has been studied by introducing vertical boreholes at various locations in the hydrogeological model applied for analyses of the temperate period in SR-Site /Joyce et al. 2010, Section 5.6/. The open boreholes were added to the SR-Site hydro base case repository-scale model as narrow vertical fractures with a width and thickness of 0.08 m. Each borehole extended from an elevation of –10 m to down to –600 m (about 130 m below repository depth).

The groundwater flow and transport was calculated using steady-state conditions based on a snapshot of boundary conditions and density at 2000 AD, as for the SR-Site hydro base case model. A freshwater density was assigned to the entire borehole, which should be a conservative assumption in terms of hydraulic driving forces. For each case, particle tracking was carried out and performance measures were calculated for all canister locations within the modelled repository block. The results were then compared with the hydro base case.

The results show that the presence of an open borehole has an effect on the flow pattern in the model. A borehole through the backfill and buffer above a canister will act as a sink for many flow paths and the water flow in the borehole is directed upwards. In all cases but one, particles are attracted to the borehole. These results take into account all unique particles that enter the boreholes even if the path length along the borehole is short. In almost 50% of the modelled cases more than 5% of the released particles at some point enter the borehole and in 25% of the cases, more than 10% of the particles enter the borehole. It is not possible to draw any conclusion about the sensitivity to boreholes for the different blocks based on the results since the frequency and locations of boreholes vary between the blocks. However, it is concluded that it is not difficult to find positions for boreholes, inside or outside deposition tunnels and inside or outside fracture zones, which will have a considerable effect on the number of particles captured by the borehole. In fact, even if the borehole is drilled in the rock outside deposition tunnels and fracture zones, there will still be particles entering the borehole through the fracture network at all elevations.

Although the flow paths are affected by the borehole, statistical analyses of the results indicate only small effects of the borehole on the performance measures for flow paths through the deposition tunnel backfill into fractures intersecting the deposition tunnel (Q3-path) as compared with the SR-Site hydrogeological base case model /Joyce et al. 2010, Section 6.3.6/. The change in performance measures generally stays within 20% comparing the borehole case with the hydro base case. The performance measures behave as expected, initial Darcy flux and equivalent flow rate is slightly increased whereas the travel time, path length and F is somewhat decreased in the borehole cases. When the statistical analysis is performed on only the particles that enter the boreholes and the results are compared to the same subset of particles in the hydro base case, the effect on the performance measures is larger. However, the changes still remain within a factor of 4 and in the same direction for the different performance measures as before. This indicates that the flow paths established by the presence of the borehole have similar transport characteristics to the flow paths without a borehole. Furthermore, the upward directed flow in the borehole implies that reducing conditions prevail inside the penetrated canister. The modelling results do not show explicitly where the flow paths continue from the borehole, but the interpretation is that the water in the borehole exits into the highly transmissive fractures in the upper part of the bedrock and continues towards low points in the terrain.

6.3.4 Uncertainties

Dose from canister penetrated by drilling

As discussed in preceding chapters, both future societal conditions and technical practices are unknown. The analyses are based on the worst plausible situation given current habits and practise. There are a number of uncertainties in the assumed drilling case regarding the impact on the deposition hole hit by the drilling and in the calculations of the doses that this action gives rise to.

One major uncertainty concerns the amount of the inventory brought to surface by the drilling, and especially the amount of the dose-dominating radionuclide Ag-108m. In the calculations it is assumed that the whole inventory of Ag-108m is instantaneously released from the spent fuel and brought to the surface by the drilling. This is a pessimistic assumption, since Ag-108m is contained in metal parts of the fuel and would thus be brought to the surface in a quantity proportional to the amount of fuel brought to the surface. The assumed radius of the borehole will also affect the amount of radionuclides brought to the surface, and the handling of the fuel and cuttings will affect their spreading and dilution in the biosphere. For example, unbroken fuel rods may be removed from the site for further inspections instead of left on the ground as is assumed in the calculations. All these factors will affect the calculated doses from the fuel and cuttings left on the ground.

One important uncertainty related to the concentration of radionuclides in the water in the borehole concerns the buffer properties after the drilling event. The borehole is assumed to penetrate both the deposition tunnel and deposition hole and the borehole is grouted and remains open. Based on current practise and the assumed drilling angle this would be a plausible situation. However, usually a smaller drilling angle is used and, if this was the case, it would be more probable that the borehole would penetrate the buffer and canister only and not the deposition tunnel. In such a case, it is probable that the borehole would not be grouted, that most of the buffer material would remain in the deposition hole and that there would be diffusion resistance in the buffer. This would imply greatly reduced releases of radionuclides to the well water. Other uncertainties concern the magnitude of the flow through the penetrated canister, the direction of the groundwater flow in the borehole and the chemical conditions inside the penetrated canister, which affects the release of radionuclides from the fuel to the groundwater. Concerning flow direction, the assumption is that the borehole is used as a well and consequently the direction of the flow is in towards the borehole and then upward to the surface. The results of the hydrogeological modelling of this borehole case /Joyce et al. 2010, Appendix G/ indicate that the flow in the borehole is directed upwards towards the surface also when pumping in the borehole is not considered. This supports the use of a fuel alteration rate applicable for reducing conditions. The magnitude of the flow through the penetrated canister is pessimistically chosen based on results of hydrogeological modelling.

Other uncertainties regarding the calculated dose to the drilling personnel and the annual effective doses to the family concern the following.

- The time of the drilling.
- The time the family settles at the site.
- The availability in, and loss of, radionuclides from the contaminated soil.
- The use of the borehole and contaminated ground and the time the person spends in the contaminated area.

The time of the drilling is set to be at the earliest 300 years after deposition. This basically affects the radionuclide inventory; the earlier the drilling takes place, the larger the inventory of short-lived radionuclides and the higher the annual effective doses.

The shorter the time between the drilling event and the time when the family settles at the site, the more radionuclides will remain in the contaminated area on the ground and the larger the inventory of short-lived radionuclides in the well-water.

The whole radionuclide inventory in the contaminated area is assumed to be instantaneously available for transfer to the agricultural production and air with contaminated dust. This assumption leads to a pessimistic value of the annual effective dose, since most likely only a fraction of the inventory will be available from the beginning. Further, it is assumed that there are no losses of radionuclides from the contaminated area other than by radioactive decay. However, in reality, other loss processes, such as leaching in percolating waters, are likely to be of importance. Note that the calculated annual effective dose from the radionuclides brought to the surface is valid only for the first year after the intrusion given these assumptions and that the land is assumed to be cultivated during that year.

It is not certain that the family finds the borehole and uses it as a well. Current practice is to place the pump just above the borehole for the well. Non-manual pumps are most often covered and some space is left around them to allow maintenance. Manual pumps require some space for pumping. The combination of using the borehole as a well and the contaminated soil from the area around it for cultivation therefore seems unlikely. Based on current practice the most likely situation seems to be that the contaminated area will either be used for cultivation or the borehole will be used as a well. Consequently, the person can be assumed to either receive the dose from the use of the contaminated area for agricultural purposes or from using the borehole as a well.

Impact of borehole on other parts of the repository

Uncertainties in the analyses of the impact of the borehole on other parts of the repository than the deposition hole directly affected by the borehole is judged as small compared with those associated with the calculations of dose from the canister penetrated by the drilling. The conclusion that a borehole through the backfill above, and buffer in, the deposition hole hit by drilling does not affect the backfill and the buffer in a neighbouring deposition hole, is based on results of analyses reported by /Åkesson et al. 2010, Appendix F/. These analyses addressed loss of backfill above a deposition hole or in the middle between two deposition holes. Although the results reported by /Åkesson et al. 2010/ are associated with uncertainties, their results in combination with the situation in this case, where a potential loss of backfill occurs still further away from a deposition hole, seem firm enough for the conclusion drawn.

The study of the impact of open boreholes on the groundwater flow in and around the repository was performed on a repository block by block basis, i.e. the repository was divided into three blocks and each of the three repository blocks was modelled separately. Potentially a borehole could have an effect on the other parts of the repository which would not be captured in these models. However, it is judged that this would not significantly change the statistical results.

In the hydrogeological models, the boreholes were assigned geometrical and physical (conductivity and porosity) properties that were chosen in order to make a good enough numerical representation of a borehole. The exact values of the parameters are difficult to define, but given the stylized nature of the results obtained the current values are judged sufficiently well established. Also, a freshwater density was assigned to the entire borehole, which should be a pessimistic assumption in terms of hydraulic driving forces.

Particle tracking was only carried out within the repository-scale model, since the effect of boreholes is likely to be local and, consequently, the effects should be most significant at the repository scale.

6.3.5 Conclusions

If a canister is penetrated and the borehole is used as a well for drinking and irrigation, the annual effective doses to representative members of critical groups will exceed the individual limit on annual effective dose for members of the public but not the annual effective dose due to background radiation. Assuming the site-specific median water yield of percussion holes drilled in the repository rock at Forsmark, the dose corresponding to the regulatory risk limit is exceeded if the intrusion occurs during the first c. 35,000 years after repository closure.

If the instant release fraction and crushed material, pieces, and even unbroken fuel rods, from the fuel elements are brought to the surface by drilling, the persons executing the drilling will receive very high doses. After a couple of hours of exposure, the limit on 1 Sv for suffering from radiation sickness is exceeded. Further, if the contaminated soil surrounding the borehole is used for agricultural purposes, the exposed persons in the case illustrated may be severely injured. However, as discussed above, the case analysed involves a number of simplified and cautious assumptions and the calculated annual effective doses should be seen as illustrations of possible consequences rather than estimations of what the consequences would be.

An open borehole might affect the long-term properties of the backfill in the deposition tunnel in the vicinity of the borehole but the effect on the backfill above neighbouring deposition holes is assessed as negligible. This implies that the buffer surrounding canisters in neighbouring deposition holes in the deposition tunnel is also unaffected by the borehole. An open borehole through the backfill will also change the pattern of flow paths in the rock beneath the highly transmissive fractures in the upper part of the bedrock. However, the new paths established have similar transport characteristics as those prevailing without an open borehole through the backfill. The change in performance measures generally stays within a factor of four comparing the borehole case with the hydro base case for the SR-Site main scenario. Therefore, it is judged that even if drilling a borehole that penetrates a canister will severely affect the deposition hole hit by drilling, the impact of the borehole on the containment potential of other parts of the repository as well as on the retardation potential of the geosphere is negligible.

6.4 Assessment of the rock excavation or tunnel case

6.4.1 Introduction and specification of the case analysed

As discussed in Chapter 4, there are several plausible reasons for constructing tunnels or other types of underground excavations in the bedrock. Today, facilities are built below the rock head to protect the activities or objects the underground excavation is meant to accommodate from activities or conditions occurring at the surface or *vice versa*. Underground excavations can also be built if considered advantageous from an economic or resource consumption point of view. This can be due to high economic, ecological or cultural values of the land or due to climate conditions. For example, it can be beneficial from an economic point of view to accommodate an activity requiring an even temperature, e.g. cold or warm storage, below the surface.

The impact on the repository of the construction and operation of a rock excavation or a tunnel at, or close to, the repository site will depend on the depth and size of the excavation. The impact will also depend on the purpose of the excavation i.e. the activities taking place there, the constructions made, the equipment used, the material stored etc. In relation to the assessment period of up to one million years, the operation of the facility can be assumed to go on for a short period, in the order of 100 years. Constructions and equipment may, however, be left in the excavation after it is no longer in operation.

The larger and deeper the facility, the greater the potential impact on the repository. Today, existing and planned underground excavations constructed to repository depth of 400 metres or deeper include mines, hard rock laboratories and deep geological repositories for radioactive material. These kinds of facilities are considered unrealistic at or close to the repository site. Mines are excluded, since sites including exploitable natural resources are excluded in the site selection. Hard rock laboratories and deep geological repositories are excluded, since it is probable that societies planning the construction of these kinds of facilities will discover and understand that the site is already used for a similar purpose and either construct their facility so that is does not intrude on the existing one or chose another site. For the other kinds of facilities mentioned in Table 4-1 the depth is generally as shallow as possible with regard to the geology and purpose of the facility. Generally, tunnels are constructed down to a depth of 50 metres, which is considered to be plausible also at Forsmark. This is, for instance, the depth of the final repository for low- and intermediate level waste (SFR), located close to the planned final repository for spent fuel.

For most purposes, tunnels or rock excavations are sealed to prevent water inflow and reinforced to mechanically stabilise the tunnel and to avoid the fallout of rock blocks when they are in operation. In many cases, the tunnel walls are lined with concrete. If the tunnel is used for final storage, it is assumed that measures are taken to prevent hazardous quantities of the unknown stored material to escape from the tunnel.

The size of a tunnel or rock excavation depends on its purpose. Tunnels can have cross sections from about four up to 100–200 m^2 and excavations can have volumes from 10,000 to 100,000 m^3 or more.

Based on these elaborations, the following case is analysed.

- A tunnel is constructed at 50 metres depth with a cross section of 100 m^2 and with a length corresponding to the whole repository footprint along the centre line of the deposition areas is considered. The justification of this assumption is that it is plausible in relation to current practice and does not underestimate the possible impact on the repository.
- The purpose of the tunnel or rock excavation is not specified.
- The operational phase of the tunnel and the designed working life of sealing and reinforcement is assumed to be a couple of hundred years. After operation, it is assumed that the tunnel is abandoned and saturated with groundwater.
- As in the drilling case, it is assumed that the existence of the repository is forgotten and that the technical standards for making underground constructions are similar to those used at the present. Further, it is assumed that the construction of the rock excavation (tunnel) is not initiated before 300 years after repository closure.

6.4.2 Assessment of the consequences of the construction of a tunnel above the repository

At Forsmark, the bedrock selected for hosting the final repository for spent fuel (the target volume) comprises the north-westernmost part of a tectonic lens (Figure 6-4). The upper part of the bedrock (down to about 150 metres depth) in the target volume is recognised for its large horizontal fractures/sheet joints /SKB 2008/. Due to these structures and the high fracture frequency close to the rock head, the upper part of the bedrock is much more water conductive than the lower part, especially below 400 metres depth. A measure of the hydraulic importance of these sheet joints in the upper part of the bedrock is provided by the exceptionally high water yields in the percussion boreholes drilled during the site investigation. The median yield of the first 22 percussion-drilled boreholes is c. 12,000 L/h /SKB 2008, Section 8.4.4/. This is c. 20 times higher than the median yield of the domestic water wells drilled outside the tectonic lens, which is no different from the median yield of all bedrock wells registered at the Geological Survey of Sweden /SKB 2008, Section 8.4.4/. The high water yield at shallow depth in the target volume of the bedrock inside the

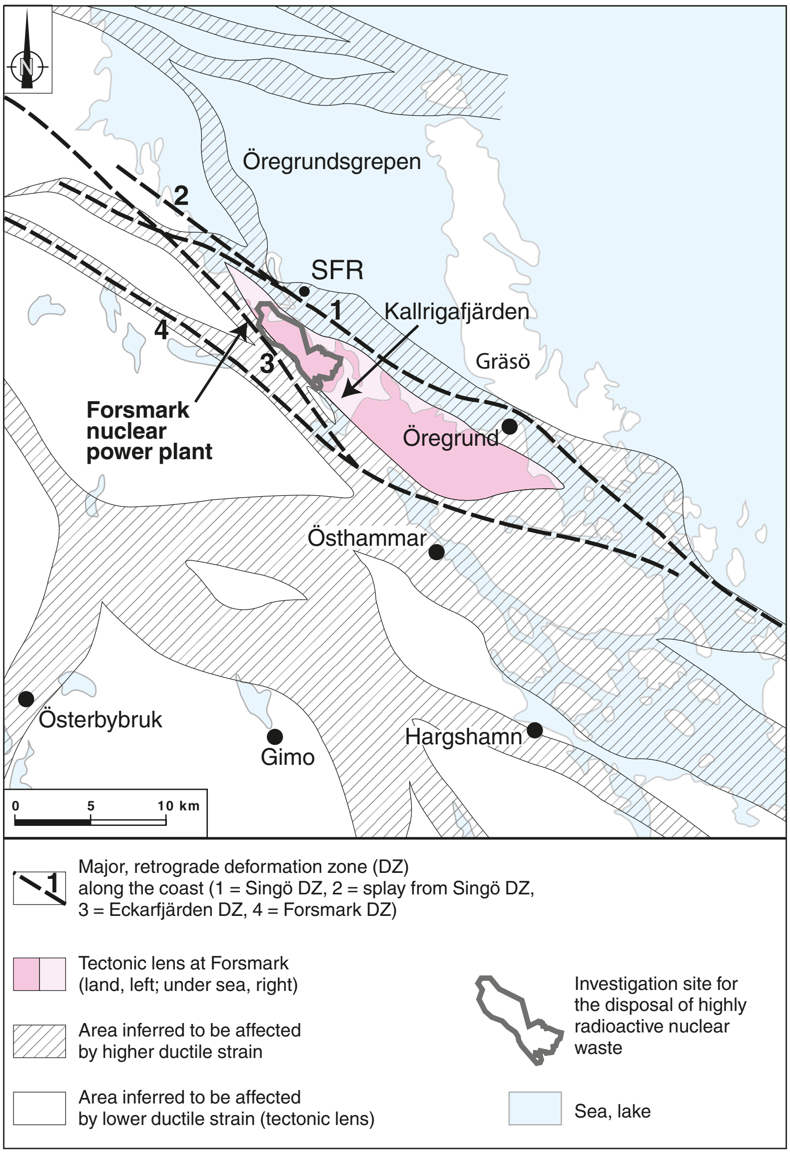


***Figure 6-4.** Tectonic lens at Forsmark and areas affected by strong ductile deformation. The planned location of the deep repository is in the north-westernmost part of the tectonic lens in the northwestern part of the site investigated. The major deformation zones surrounding the lens are also marked (Figure 4-1 in /Stephens et al. 2008/).*

tectonic lens is not only due to these large horizontal structures in the upper part of the bedrock and the high fracture frequency close to the rock head, but also due to the closeness to the sea, which acts as an endless source of water (positive hydraulic boundary).

If a tunnel is constructed at 50 metres depth, despite the high conductivity in the upper part of the bedrock in the target volume, this would place limitations on constructability and require extensive grouting. Grouting would, in turn, considerably limit the impact of the tunnel on the hydrogeology in the surrounding superficial rock. There is no reason to expect that an open tunnel at 50 metres depth located above the repository should result in up-coning of groundwater that would significantly affect the hydrogeology in the repository bedrock at 450 metres depth. This conclusion is supported by the significant decrease in the frequency of water-conducting fractures with depth observed in the site investigations. It is noted that not even the spent fuel repository is expected to give noticeable up-coning during the construction and operation phase, as shown by modelling results for an open repository reported in /Svensson and Follin 2010, Section 5.2/.

The future shoreline displacement at Forsmark during the next 1,000 years is on the order of 7 m /SKB 2010i/. This decrease in shoreline elevation is not expected to change the importance of the horizontal fractures/sheet joints in the upper part of the bedrock for the hydrogeological system in the target volume of the rock as the horizontal fractures/sheet joints in the upper part of the bedrock occur also at greater depths than 7 m. Potential construction and operation of a tunnel above the repository during the next 1,000 years would then not negatively impact the performance of the repository. Abandoning the tunnel during this period would imply that the tunnel becomes filled with water as the grout in the tunnel degrades. The abandoned tunnel might act as a conductor for near-surface flows, but no significant impacts on the magnitude of the water flow in the rock surrounding the deposition holes in the repository is expected. This is based on the results from hydrogeological analyses of an abandoned, partially open repository /Bockgård 2010/, which show very small changes in the magnitude of Darcy flux at deposition hole positions if it is assumed that all excavations in the repository except deposition tunnels and deposition holes are open, as compared with the expected case that the repository is completely backfilled and sealed. These results are further discussed in Section 6.6.3. Consequently, there is little reason to expect that an abandoned open tunnel restricted to 50 m depth should impact the magnitude of the water flow at repository depth. Furthermore, similar arguments could be made for tunnels located down to at least the 150 m level.

6.4.3 Conclusions

The above assessment indicates that the upper 150 m of the bedrock above the repository is an unfavourable location for a tunnel from en engineering point of view, due to the exceptionally high water yield in this part of the bedrock. These conditions also imply that a tunnel constructed in this part of the bedrock would not affect the groundwater flow at repository depth such that the presence of the tunnel violates the safety functions of the deep repository. The design consideration to locate the repository at a depth that allows utilisation of the site for generally occurring future human activities should, therefore, be fulfilled at Forsmark.

6.5 Assessment of a mine in the vicinity of the Forsmark site

6.5.1 Introduction and specification of the case analysed

The ore potential at Forsmark has been analysed within the site investigations. In an area south-west of the Forsmark site a felsitic to metavolcanic rock, judged to have a potential for iron oxide mineralisation, has been identified /Lindroos et al. 2004/ (see Figure 6-5). The mineral deposits have been assessed to be of no economic value. Nevertheless, as this judgement may be revised in the future due to economic reasons, the potential exploitation of this mineralisation is addressed.

Since the mineralisation at the present is judged to be of no value, it is impossible to describe the design of a mine exploiting the mineralisation based on current mining standards. It could be a quarry or a mine and the depth could be from tens to hundreds of metres or for mines a thousand metres or even deeper.

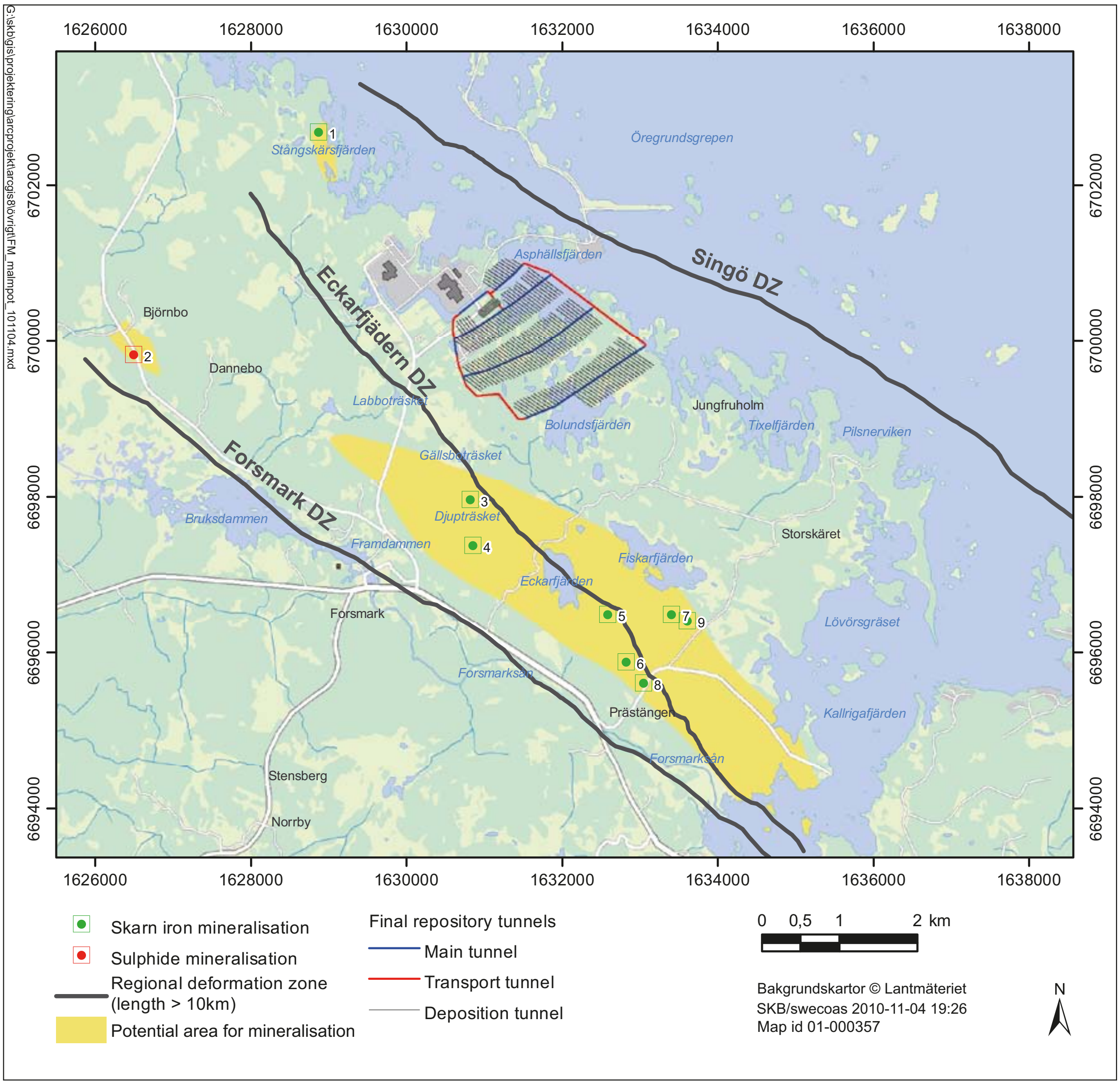


Figure 6-5. *Map showing the areas on the surface that are judged to have some exploration potential for mineral deposits (modified after Figure 5-4 in /Stephens et al. 2008/).*

6.5.2 Assessment of the consequences of a mine in the vicinity of the Forsmark site

If a mine, or other sub-surface rock excavation, were to be constructed in the vicinity of the Forsmark site, it may be assumed that the greatest influence on the repository for spent nuclear fuel would occur if the construction took place at the same depth and in close proximity to the repository for spent nuclear fuel. Since the south-westernmost part of the repository is located west of Lake Bolundsfjärden (Figure 6-5), the closest distance between the repository and a hypothetical mine in the potential area for mineralisation (Figure 6-5) would be on the order of 1 to 1.5 km.

In order to assess the potential influence on the repository, results from analyses of the hydraulic impact of an open repository are used. Calculations of the effects of water inflow to an open repository show that the drawdown of the hydraulic head is large in the rock close to the repository at a depth of 450 m /Mårtensson and Gustafsson 2010, Figure 7-20 lower insert/. However, the drawdown decreases rapidly with distance from the open repository in a westerly direction to about 50 m within tens of metres from the repository and at distance of c. 1 km from the repository, the drawdown at 450 m depth is negligibly small. The reason for the small radius of influence is the low hydraulic conductivity of the rock mass volumes at depth in proximity of the repository. This constraining hydraulic condition is valid also for a potential future mine outside the tectonic lens. Therefore, it is reasonable to expect a very limited hydraulic impact from the mine on the repository because of the low conductivity bedrock in the target volume.

6.5.3 Conclusions

The assessment indicates that exploitation of the potential mineral resources in the vicinity of the Forsmark site would not impact the safety functions of the repository. The design consideration to locate the repository at a site without natural resources is, therefore, considered to be fulfilled.

6.6 An incompletely sealed repository

6.6.1 Introduction and specification of the case analysed

According to regulations, it is also necessary to define and analyse a case that illustrates the consequences of an unsealed repository /SKI 2002/. The basic assumption in the case selected as representative for scenarios related to an unsealed or incompletely sealed repository is that the repository is abandoned when all canisters are deposited and all deposition tunnels backfilled and sealed, but the main and transport tunnels as well as the central area, repository access (ramp and shafts) and the ventilation shafts in the deposition area (see Figure 6-6) are still open due to, for example, political decisions not to seal completely. This assumption is based on the strategy for deposition of canisters, which implies that deposition tunnels are successively filled with canisters and then backfilled and sealed as soon as they are filled. Abandoning the repository in the middle of this process is judged as rather unlikely because this would mean that canisters are left at the surface where they would constitute a larger risk than if emplaced in the repository.

An outline of the case analysed is provided below.

- The central area, tunnel system, ramp and shafts are open to groundwater circulation.
- The plugs at the end of the deposition tunnels rapidly loose their function and the backfill swells out into the water flowing in the main tunnels.
- Water flowing in the main tunnels is saturated with air and oxygen dissolved in the water may be transported to canisters in the deposition holes. In addition, canister corrosion occurs by sulphide dissolved in the groundwater.
- The canisters corrode, and after corrosion breakthrough, nuclides are transported out into the water flowing through the open tunnels and further up to the ground surface.
- Water in the open ramp and shafts is used by humans who are exposed to radionuclides in the water.

6.6.2 Qualitative description of the consequences of a not completely sealed repository

If the repository is abandoned when the main and transport tunnels, central area, repository access and ventilation shafts in the deposition area are still open, these open volumes will successively become water filled. Water will flow through the open volumes with a magnitude and direction dependent on the magnitude and direction of the hydraulic gradient. In addition, the open volumes may affect the groundwater flow pattern in the repository bedrock.

All deposition tunnels will be plugged towards the main tunnels when the repository is abandoned. When the main tunnels have been filled with water, the cement and other components in the concrete plugs may be dissolved in the water and transported away. At some point in time the plugs will lose their function and the backfill in the deposition tunnel will swell out into the main tunnels. This swelling out into the main tunnels will decrease the density of the backfill in the deposition tunnels. How far into the deposition tunnel the decrease in density reaches depends on the amount of backfill material that is lost from the deposition tunnel. If the density in the backfill above a deposition hole is significantly reduced, the buffer in the deposition hole may expand into the backfill above with the consequence that the density of the buffer also decreases. A possible implication of such a reduction in density of the buffer is that advection becomes the dominating process for solute transport in the buffer instead of diffusion.

Abandoning the repository without sealing the access from the surface may facilitate recharge of oxygenated water from the surface down to the central area and the main tunnels. In addition, the unsealed parts of the repository will contain air which will dissolve in the water that successively intrudes into the empty, unfilled parts of the repository. If dissolved oxygen reaches the canisters via the backfill in the deposition tunnels and the bentonite buffer or via fractures in the rock that intersect the deposition tunnel and further through the bentonite buffer, the oxygen will corrode the copper canisters. This may lead to corrosion breakthrough in the canisters and release of radionuclides from the spent fuel.

If and when corrosion breakthrough occurs depends on the supply of oxygen to the canister surface. Groundwater recharging from fractures and fracture zones intersecting the unfilled volumes deeper down in the rock will most likely not contain dissolved oxygen due to the large reduction capacity of both the rock and the overburden through which this water has infiltrated. The major supply of oxygen from the surface down into the open volumes of the repository will likely occur during glacial periods when glacial meltwater can be forced down due to the high hydraulic gradients established by the ice sheet. However, oxygen dissolved in the water in the empty volumes of the repository may also be consumed by both biotic and abiotic processes. For example, biological degradation of organic materials, already present in the empty volumes as well as supplied with incoming water, will continue until either the oxygen or the biodegradable organic material is depleted, and oxygen may react chemically with reducing minerals in the rock such as chlorite, biotite and pyrite /Sidborn et al. 2010/, as well as be consumed by aerobic corrosion of iron construction materials left in the unfilled volumes of the repository.

Further transport of dissolved oxygen from the unfilled main tunnels in the repository to the canisters in the deposition holes will take place by advection or diffusion in the backfill in the deposition tunnels and in the bentonite surrounding the canisters, depending on the properties of these barriers. Alternatively, transport of dissolved oxygen may take place with groundwater flowing in fractures that intersects the deposition holes and are connected either to the unfilled main tunnel or to the deposition tunnel at a location close to the intersection with the main tunnel (see Figure 6-6). Both in the backfill and the buffer, oxygen consumption may take place by chemical reactions with accessory minerals in the bentonite. In addition, microbial activity in the backfill is expected to consume oxygen.

The groundwater at Forsmark contains sulphide that can corrode the canisters. In addition, the bentonite contains organic materials that under anoxic conditions potentially could be utilised for microbial reduction of sulphate in the groundwater to sulphide /Hallbeck 2010/. As long as the backfill above a deposition hole does not lose density to the extent that the buffer in the deposition hole can expand upwards into the backfill, microbial sulphate reduction in the bentonite buffer is not expected to take place to any extent. If the backfill density is reduced to such extent that the buffer can expand upwards into the backfill, the buffer density may become too low to rule out microbial activity in the buffer. Although the amount of organic material in the bentonite accessible for microbial degradation is highly uncertain, it consists mainly of humic and fulvic acids that have molecules that are too large molecules to be used by bacteria as carbon source.

6.6.3 Analyses of barrier functions and groundwater flow

Analysis of expansion of deposition tunnel backfill

The expansion of backfill in deposition tunnels out into the main tunnel has been analysed by /Åkesson et al. 2010, Section 22/. After disintegration of the plug there will remain a substantial part of the components of the plug, since both the sand filter and the concrete ballast material will not dissipate but is expected to remain as a soil heap. However, since it is likely that the lack of support from a backfill outside the plug will make the particles fall down to some kind of angle of repose, there may be a large opening in the upper part of the plug where bentonite freely may swell out into the transport tunnel. Since the size of this opening is difficult to predict it is pessimistically assumed that the entire plug is lost.

The free swelling of the backfill out of the deposition tunnel and into the main tunnel will be driven by the swelling pressure of the backfill and counteracted by the friction between the backfill and the rock surface and the swelling of backfill from the other tunnels. The swelling is assumed to be similar from the other tunnels and thus stopped halfway between the deposition tunnels, i.e. the backfill cannot swell more than 20 metres along the transport tunnel since the distance between

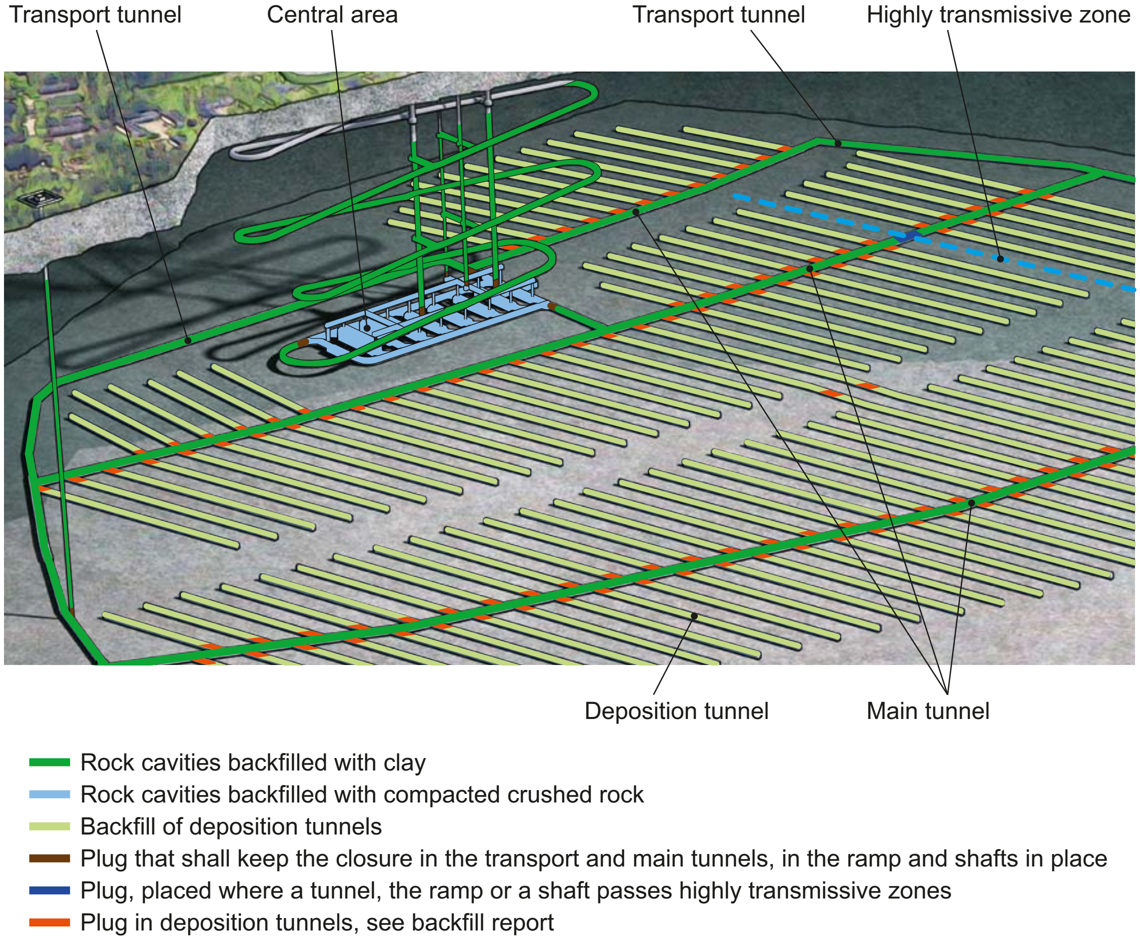


Figure 6-6. *Reference design for repository closure (Figure 3-1 in /SKB 2010e/). In this case it is assumed that only the deposition tunnels are backfilled and plugged towards the main tunnels.*

the tunnels is 40 metres. The geometry of the tunnels outside the plug where the swelling will take place is shown in the lower part of Figure 6-8 and the simplified geometry used in the calculations is illustrated in Figure 6-7.

The results of the analyses indicate that a backfill with an initial dry density of 1,470–1,600 kg/m^3 (corresponding to a swelling pressure of 3–10 MPa) will swell out into the main tunnel and that the density in the main tunnel will be very low (area 3 in Figure 6-8); a dry density less than 230 kg/m^3. This corresponds to a water ratio of more than 400%, which is higher than the liquid limit of a Ca-bentonite and thus more like a liquid than a gel. The results of the analyses further indicate that the loss of backfill and the resulting effect on the backfill density in the deposition tunnel reaches 40 to 50 metres into the deposition tunnel from the interface between the backfill and the degraded plug (area 1 in Figure 6-8) and that deposition holes located closer than 25 to 35 m from the degraded plug/backfill interface will experience a backfill with a dry density that is below the acceptance criterion of 1,240 kg/m^3. Since no deposition hole will be located closer than 20.6 m from the deposition tunnel entrance /SKB 2009a/, this implies that the loss of backfill from deposition tunnels could lead to density reduction of the buffer in at most four to five deposition holes located closest to the tunnel entrance.

The consequences of free swelling of the backfill in a deposition tunnel for a case where the plug in a neighbouring deposition tunnel is intact and the backfill in this tunnel remains in place have not been analysed quantitatively. Clearly, more backfill will expand out into the main tunnel and it is envisaged that a few additional deposition holes will experience a backfill with a density below the acceptance criteria, as compared with the case with expansion of tunnel backfill in two neighbouring deposition tunnels. However, the exact number of such deposition holes is not important for the approach selected for analysis of the consequences of this case, see further Section 6.6.4.

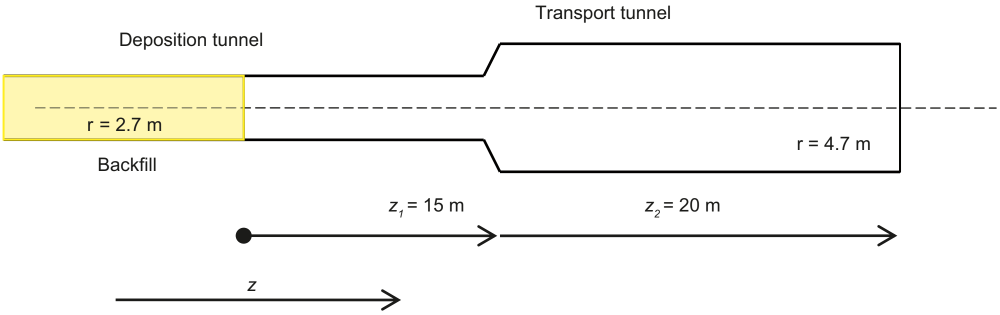


Figure 6-7. *Simplified 1D geometry used in the calculations (Figure 22-2 in /Åkesson et al. 2010/).*

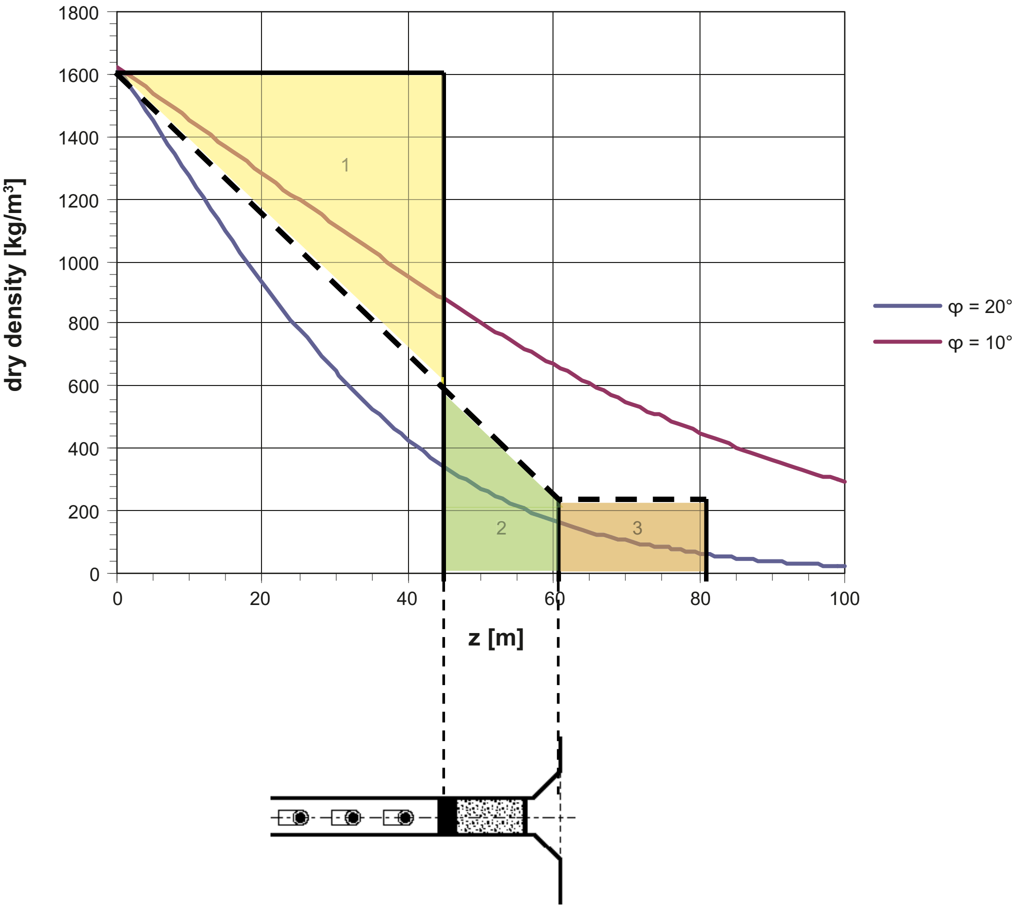


Figure 6-8. *Relation between dry density and the distance to the unaffected backfill front for a backfill swelling pressure of 3 MPa and two different friction angles. The broken line corresponds to the relation used between the distance from the swelling front and the dry density of the backfill in the deposition tunnel used to calculate the dry mass loss over distance. The coloured areas represents the different distances over which mass loss (area 1) and mass gain (areas 2 and 3) should occur to obtain mass balance (Figure 22-7 in /Åkesson et al. 2010/).*

Groundwater flow analyses

In order to investigate the hydraulic influence of an abandoned, partially open repository, as compared to the reference closure of the repository, the effects of open tunnels have been studied for two situations with different boundary conditions; a temperate situation with present-day boundary conditions and a generic future glacial situation with an ice sheet partially covering the repository /Bockgård 2010/. The boundary conditions in the glacial simulation represent a case with an advancing ice margin, but without permafrost, where the ice front is located above the repository.

The results obtained for temperate conditions indicates inflow to the open tunnel system through the ventilation shafts in the deposition area and water discharges through the ramp and shafts above the central area (see Figure 6-6 and Figure 6-12 for locations of the repository features). The water flow in the open system amounts to 0.42 L/s (13,230 m^3/year) of which c. 60% (0.26 L/s) recharges from the transmissive surface layer and sheet joints above elevation –40 m. The hydraulic gradient in the western part of the repository at repository depth is directed towards the open tunnels and the maximum distance of pressure head disturbance is about 300 m (Figure 6-9). Because of this, flow paths from the deposition holes are to a large extent recharging to the surface via the open tunnels instead of through the rock, as in the reference closure case. This also implies shorter transport length and lower flow-related transport resistance (F-factor) for these flow paths in the rock compared with the reference closure case (Figure 6-10). However, the effect on the Darcy flux in fractures at the deposition hole positions is quite small (Figure 6-11), with a small increase of about 10% in the median value of $5 \cdot 10^{-6}$ m/year obtained in the reference closure case.

The results of the simulations for the glacial case with the ice front located above the repository show a reversed direction of flow through the tunnel system compared to the temperate situation, i.e. inflow to the repository tunnel system occurs through the ramp and shafts above the central area and discharge through the ventilation shafts in the deposition area. The flow through the tunnel system is estimated to be about 250 m^3/s and is governed by the head differences. The major head losses occur in the relatively narrow ventilation shafts in the deposition area where the flow discharges (Figure 6-12, left insert). Water is injected from the pressurised tunnels into the surrounding rock with a net flow of approximately 80 L/s, and, compared to the reference case, the open tunnels caused an increased head around most of the tunnels (Figure 6-12, right insert). This affects the Darcy flux at the deposition hole positions (Figure 6-13) as well as the flow-related transport resistance (F-factor) for flow paths from the deposition hole positions (Figure 6-14) compared with the glacial reference closure case. The median value of the Darcy flux increases from $5 \cdot 10^{-4}$ m/year to $1.3 \cdot 10^{-3}$ m/year. The median value of the F-factor decreases from $3.9 \cdot 10^{4}$ year/m in the reference closure case to $1.5 \cdot 10^{4}$ year/m in the case with open tunnels and glacial conditions. The elevated hydraulic head in the open tunnels also implies that all flow paths from deposition holes enter the surface via the rock except for a few paths (less than 1%) that enters the tunnels in the north-western part of the repository where the open tunnels cause a smaller area of drawdown.

In summary, the results from the calculations imply that the open tunnels will cause a drawdown in the surrounding rock during temperate conditions, meaning that the tunnels will capture many flow paths from canister positions and thereby act as a conductor for flow to the surface. The general flow direction in the tunnels is recharge through the ventilation shafts in the deposition area and discharge through the ramp and shafts above the central area. The impact of open tunnels on the Darcy flux at deposition hole positions is, however, small. The open tunnels decrease the median transport resistance to about 30% of the reference value.

The consequences of open tunnels for the glacial conditions assumed in the calculations are, on the other hand, considerable. The high hydraulic head established by the ice sheet may cause a significant flow through the tunnel system with recharge through the ramp and shafts above the central area and discharge through the ventilation shafts in the deposition area. The high hydraulic gradient will be transmitted by the tunnels to repository depth and water will be injected into the rock. The Darcy flux at deposition hole positions will in general increase and at certain deposition hole positions, a considerable increase in Darcy flux is indicated, but the open tunnels decrease the median transport resistance in the rock with only about 50%.

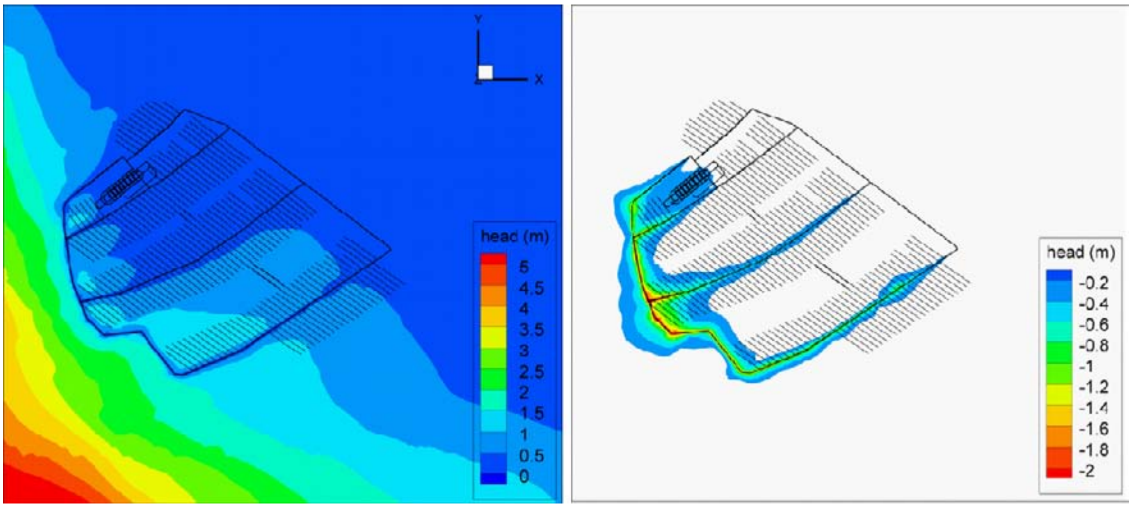


Figure 6-9. *Hydraulic head field at repository depth (elevation –465 m) during temperate conditions for the open tunnel case (left) and the change in hydraulic head caused by the open tunnels (right) (from /Bockgård 2010/).*

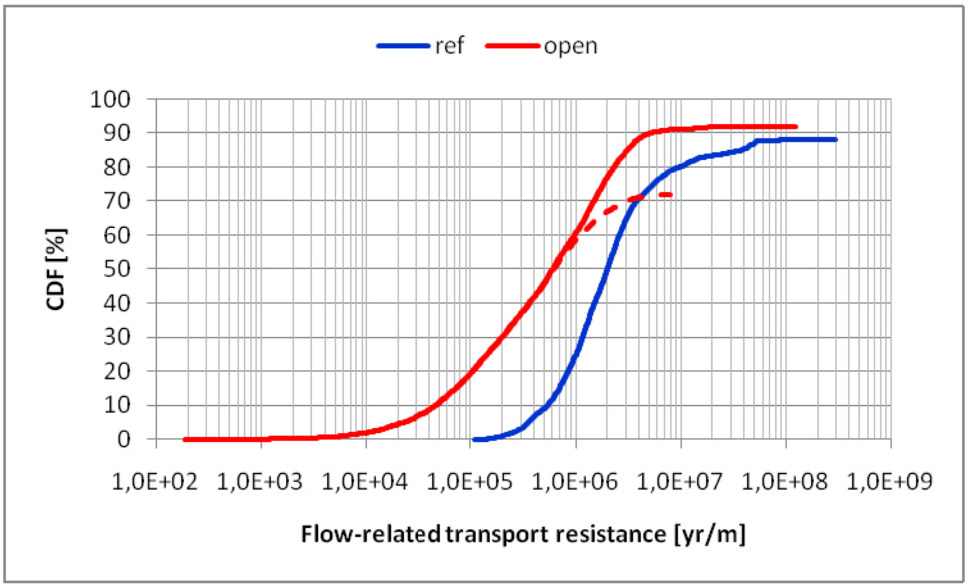


Figure 6-10. *Cumulative density function of simulated flow-related transport resistance (F-factor) for particles released at 6,916 deposition hole positions during temperate conditions for the reference closure case (blue) and the open tunnel case (red). The broken line represents the particles that entered open tunnels (from /Bockgård 2010/).*

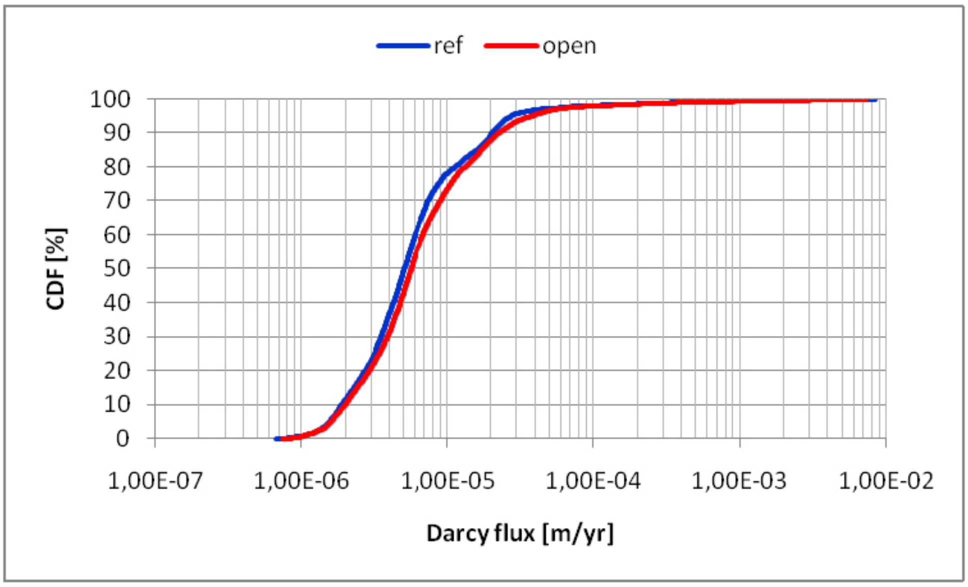


Figure 6-11. *Cumulative density function of simulated Darcy flux at 6,916 deposition hole positions during temperate conditions for the reference closure case (blue) and the open tunnel case (red) (from /Bockgård 2010/).*

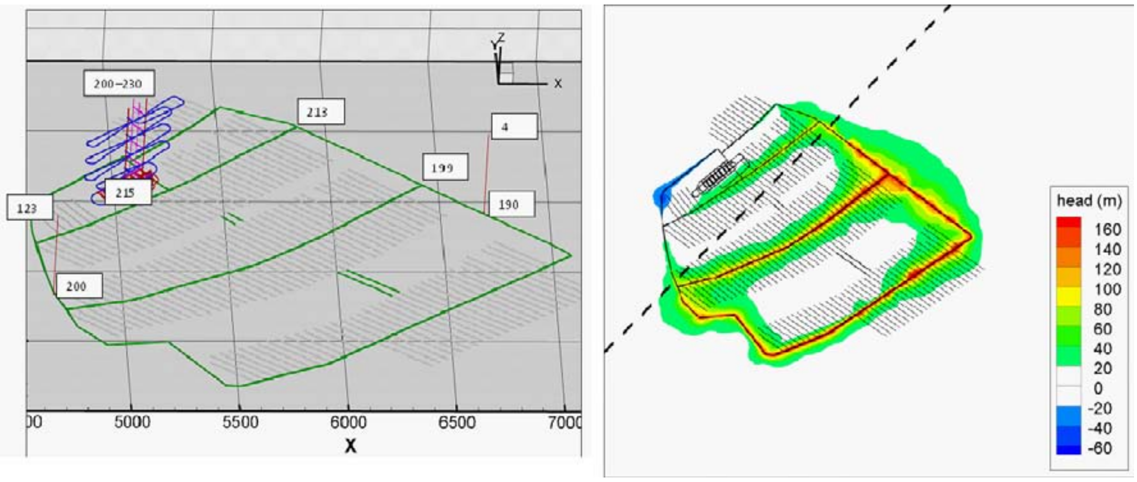


Figure 6-12. *Left: Schematic illustration of the head distribution (in metre above sea level) in the open tunnel system for the glacial case. Right: The change in hydraulic head caused by the open tunnels in the glacial case (from /Bockgård 2010/). The dashed line indicates the location of the ice front.*

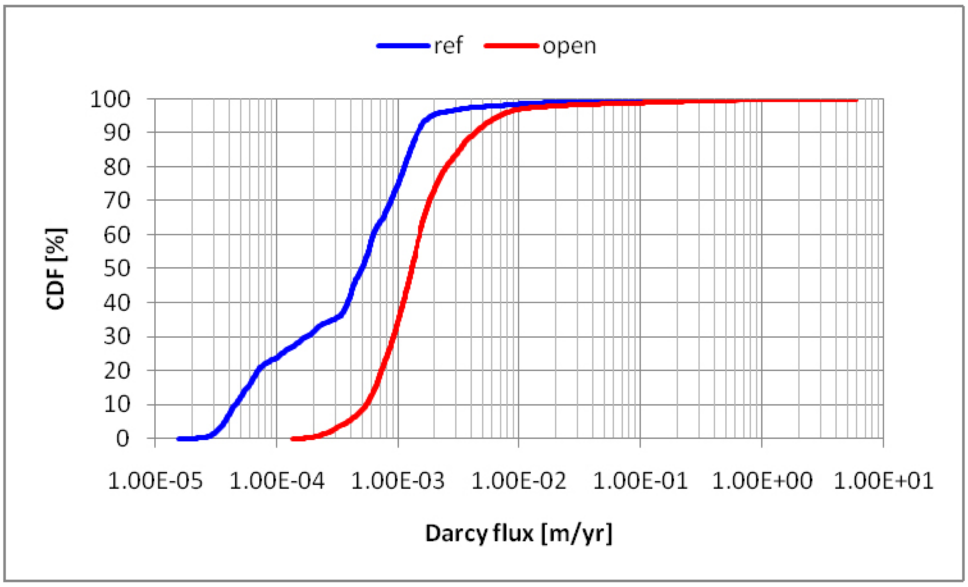


Figure 6-13. *Cumulative density function of simulated Darcy flux at 6,916 deposition hole positions during glacial conditions for the reference closure case (blue) and the open tunnel case (red) (from /Bockgård 2010/).*

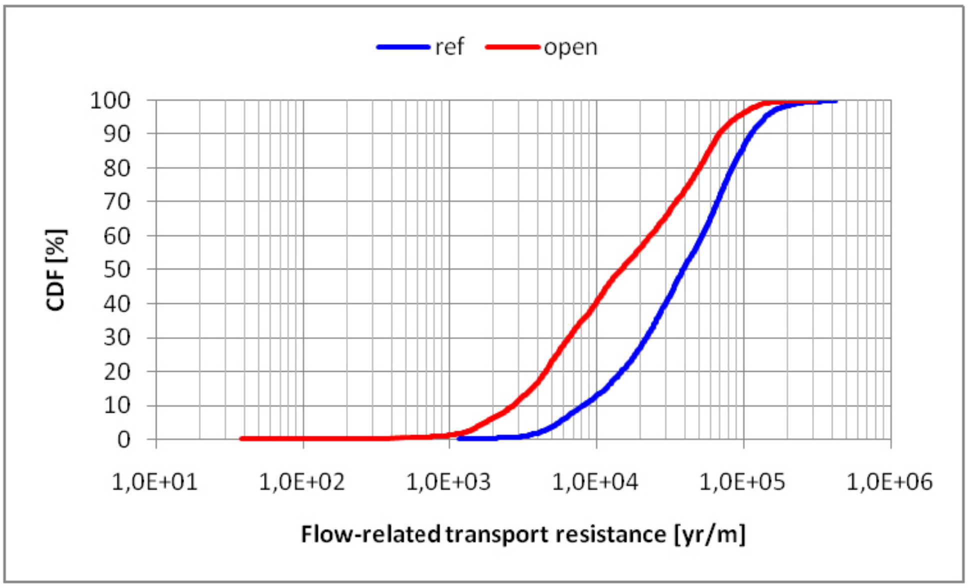


Figure 6-14. *Cumulative density function of simulated flow-related transport resistance (F-factor) for particles released at the 6,916 deposition hole positions during glacial conditions for the reference closure case (blue) and the open tunnel case (red) (from /Bockgård 2010/).*

Analyses of oxygen supply and canister corrosion

To illustrate the potential consequences for canister corrosion by oxygen dissolved in the water in the open tunnels in the repository, some simple calculations have been carried out. These calculations are described in section B3 in Appendix B. In the calculations it is assumed that the water in the backfilled deposition tunnels above a deposition hole is saturated with dissolved oxygen and that oxygen is further transported to the canister lid by diffusion through the 1.5 m thick bentonite buffer above the lid (see Figure 6-15). For temperate conditions, the concentration of oxygen at the upper boundary of the buffer is set to 0.3 mol/m^3, i.e. in equilibrium with atmospheric oxygen, and a concentration of 1.5 mol/m^3 is assumed for glacial conditions, i.e. corresponding to the concentration in glacial meltwater /Sidborn et al. 2010/.

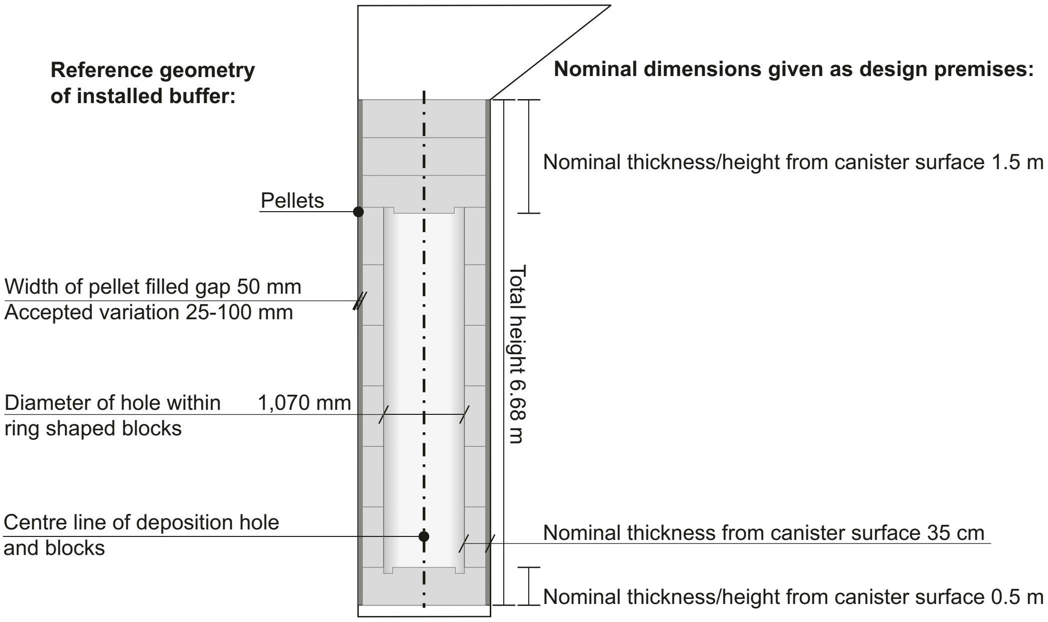


Figure 6-15. *Reference geometry of the installed buffer (Figure 3-3 in the buffer production report /SKB 2010f/).*

With an effective diffusivity of $1{\cdot}10^{-10}$ m^2/s for dissolved oxygen, an approximate value representative for uncharged species according to the SR-Site Data report /SKB 2010d/, and assuming 1D-diffusion through the entire cross-sectional area of the buffer (diameter 1.75 m /SKB 2010f/), the flux of oxygen after diffusion through 1.5 m buffer is calculated to 1.5 10^{-3} mol/year. If it is further assumed that this oxygen instantly reacts with the copper according to the stoichiometry 4 mol Cu/mol O_2, it would take 1 million years before corrosion breakthrough occurs in the 50 mm thick copper lid. If diffusion through the bentonite occurs through a cross-sectional area corresponding to the area of the canister lid, the time for corrosion breakthrough will be approximately three times longer. With a ten times higher diffusivity, representative of diffusion in unconfined water, it would still take on the order of 100,000 to 300,000 years before breakthrough occurs. With the higher concentration of dissolved oxygen, corresponding to glacial conditions, it would take on the order of 200,000 to 600,000 years for corrosion breakthrough provided that the buffer has retained its properties and about 20,000 to 60,000 years if the buffer above the canister is lost and diffusion of oxygen occurs through water only.

It should be pointed out that the estimated times provided above are very pessimistic as long as diffusion is the dominating transport mechanism in the backfill in the deposition tunnel. The calculations presume that the groundwater in the deposition tunnel above the deposition hole is saturated with oxygen which is only possible if advective transport of oxygen occurs in the deposition tunnel. As long as diffusion is dominating in the deposition tunnel backfill, it will take considerable time for the build up of an oxygen concentration above the deposition hole to the value assumed in the calculations, if it will ever occur. This is further exemplified in section B3 in Appendix B.

Sulphide as a corrosion agent is neglected in this scenario, since the corrosion breakthrough times are expected to be significantly longer than those estimated for oxygen. The main reasons for this are that the natural concentrations expected are at most in the order of 10^{-5}M /Tullborg et al. 2010/, which is order of magnitudes lower than the concentration of oxygen assumed in the simplified calculations, and that the stoichiometry of the corrosion reaction implies that less copper is consumed per mol sulphide (2 mol) compared with the consumption by oxygen (4 mol). The organic material contained in the bentonite material in buffer and backfill (see Section 6.6.2) is not expected to be utilised for microbial reduction of sulphate in the groundwater to sulphide as long as oxygen is present, if they at all are accessible to biodegradation.

6.6.4 Analyses of radionuclide release and dose consequences

Concept and assumptions

According to the reference glacial cycle evolution adopted in SR-Site and described in the SR-Site Climate report, temperate and periglacial conditions are expected for the next c. 58,000 years (Figure 6-16) /SKB 2010i, Table 4-5/. Even if the density of the buffer in deposition holes close to the intersection between the deposition tunnel and the main tunnel significantly decreases, the calculations carried out indicate that no corrosion breakthrough is to be expected within the next c. 58,000 years. Furthermore, the results of the hydrogeological analysis indicate that the hydraulic gradients during temperate conditions are directed towards the open tunnels and, hence, would act against oxygen transport from the open tunnels to the deposition holes. The hydrogeological results for temperate conditions also indicate only small effects of the open tunnels on the Darcy flux at deposition hole positions. Although the open tunnels change the flow paths with somewhat reduced flow related transport resistances in the rock as a result, these resistances are still high. The fact that flow paths are captured by the open tunnels and discharge through the shafts and ramp above the central area is also considered as insignificant, since discharge points occur close to the repository also in the reference evolution and also because periglacial conditions with permafrost in the upper parts of the ramp and shafts will prevail for large parts of the 58,000 year time period. This implies that the impact of the open tunnels for deposition holes other than those directly affected by the expanding tunnel backfill is small. Therefore, no analyses of radionuclide release and dose consequences are carried out for the period prior to the next glaciation.

At the onset of the glacial period at Forsmark (c. 58,000 years after present), the hydrogeology at the site is expected to change and high groundwater flows in the open tunnels cannot be excluded, especially when the front of the ice sheet is located above or close to the repository, as indicated by the hydrogeological analyses summarised above (Section 6.6.3). According to the reference evolution (Figure 6-16) this glacial period will last for c. 8,000 years. As shown by the results of the simple calculations described above (Section 6.6.3), no corrosion breakthrough in canisters is expected during an 8,000 year long period with glacial conditions as long as diffusion is the dominating transport process in the buffer for corrosive agents in the groundwater. For advective conditions to be established in the buffer surrounding a canister, a significant loss in buffer density is required. Furthermore, the deposition hole would have to be intersected by a fracture through which groundwater could enter or leave the deposition hole, depending on the direction of the hydraulic gradient.

During periods of high groundwater flow in the open tunnels, backfill that has expanded out into the main tunnels may be carried away. This may, in turn, result in further expansion of deposition tunnel backfill out into the main tunnels, exposing the buffer in deposition holes close to the intersection with the main tunnel to less and less counter pressure from the remaining backfill in the deposition tunnels. This may lead to expansion of the buffer upwards into the deposition tunnel, leading to a decrease in buffer density. Furthermore, if the deposition hole is intersected by a fracture large enough to carry substantial flow, buffer and backfill material could be carried away by groundwater flowing through the deposition hole and the deposition tunnel. Whether this situation is likely to occur during the 8,000 year long glacial period has not been quantitatively assessed. However, here it is assumed that it does and that this also implies that the groundwater flow through the deposition hole is large enough to supply the amount of corrosive species needed for corrosion breakthrough in the canister to occur before the end of this glacial period. This should be a cautious assumption, since permafrost prevails in the upper part of the bedrock, at least down to c.70 m depth, during the whole period (Figure 6-16), which should limit the water turnover in the open tunnels in the repository.

According to the reference glacial cycle evolution /SKB 2010i/, deglaciation at the site will occur at 66,200 AP (Figure 6-16) after which the site will be submerged during the following c. 8,000 years before periods with alternating periglacial and temperate conditions occur. In the further analysis of this case, the sequence of submerged and alternating periglacial and temperate conditions is not considered. Instead it is for simplicity assumed that temperate conditions prevail when calculating the radionuclide release from the repository and the subsequent dose impact.

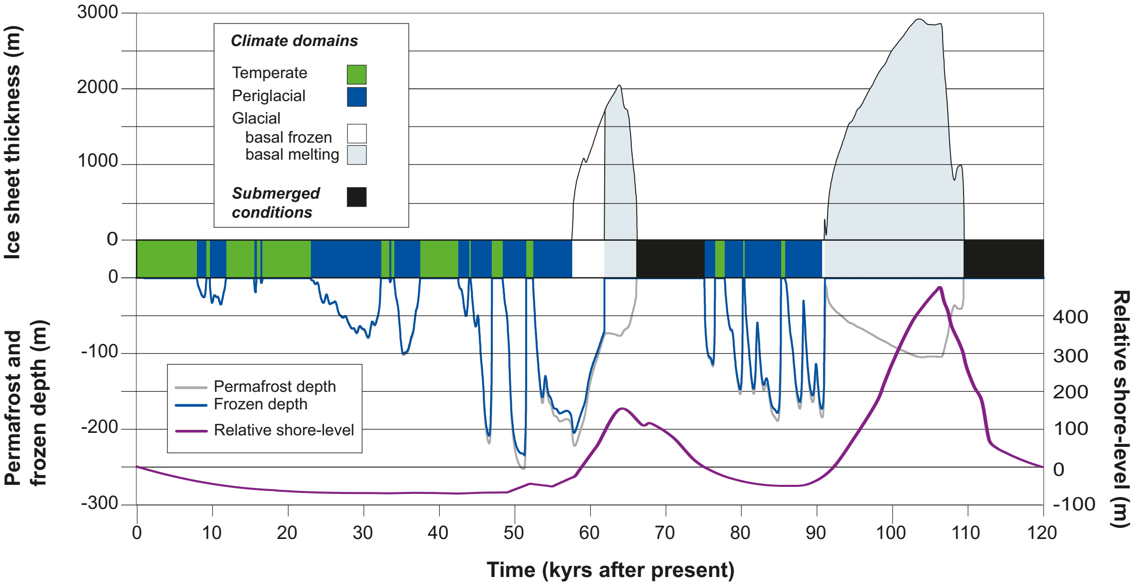


Figure 6-16. *Evolution of important climate-related variables for the coming 120,000 years at Forsmark (Figure 4-34 in the SR-Site Climate report /SKB 2010i/).*

In summary, the assumptions made in the analysis of radionuclide release and subsequent dose impact are as listed below.

- No corrosion breakthrough in canisters occurs during the first period of temperate conditions lasting until c. 58,000 years after present.
- During the subsequent glacial period lasting until 66,200 years after present, corrosion breakthrough occurs in one canister in a deposition hole that is intersected by a fracture with high groundwater flow and which is located close to the intersection between a deposition tunnel and an open main tunnel.
- At year 66,200 after present, radionuclides are released from the spent fuel in the failed canister at a rate determined by the advective flow in the fracture intersecting the deposition hole. The released radionuclides are transported with the flowing water from the deposition hole to the central area and the access ramp and shafts above the central area via the deposition tunnel and open main and transport tunnels. The concentration of radionuclides in the water in the open system is determined by the groundwater turnover in the open tunnels as estimated for temperate conditions.
- The water in the access ramp and shafts are utilised by humans for agricultural purposes and as drinking water.

Radionuclide release calculations

The release rate of radionuclides from the spent fuel in a failed canister at 66,200 years after present is calculated using the same model as that used for deterministic calculations of the central corrosion case in the SR-Site scenario “canister failure due to corrosion” (Chapter 4 in the SR-Site Radionuclide transport report /SKB 2010c/. In the calculations, no credit is taken for any transport resistance in the failed canister or in any buffer material that still remains in the deposition hole. Hence, the release rate of radionuclides from the failed canister is determined by the release rate from the fuel and the water flow in the deposition hole. The water flow in the deposition hole is set to 0.73 m^3/year. This value represents the flow in a deposition hole that is intersected by a fracture with high water flow in the analyses of the SR-Site scenario “canister failure due to corrosion”. Since the impact of open tunnels on the advective flow at deposition hole positions is quite small during temperate conditions, as indicated by the small impact on Darcy flux in Figure 6-11, this value is judged as adequate for use in these calculations.

The inventory of radionuclides in the spent fuel in the failed canister is that derived for an average canister, as reported in /SKB 2010c/ and which is based on the inventory justified and provided in the SR-Site data report /SKB 2010d/. Radionuclides in the spent fuel are contained in the uranium dioxide matrix, but also in metal parts of the fuel. In addition, the spent fuel contains fission gases that are rapidly released. In the calculations it is assumed that some radionuclides, the instantaneous release fraction (IRF), are immediately released. Radionuclides in the metal parts of the fuel are assumed to be released at a rate of 10^{-3} per year, which is the median value for corrosion-determined release from metal parts as provided in the SR-Site data report /SKB 2010d/. The release of radionuclides contained in the uranium dioxide matrix is determined by the fuel alteration rate. The fuel alteration rate assumed in the calculations is 10^{-7} per year, which is the median value for reducing conditions as provided in the SR-Site data report /SKB 2010d/.

In the calculations it is further assumed that radionuclides released from a failed canister are transported to the central area and the open shafts and ramp above the central area. The concentration of radionuclides in the water is calculated from the release rate of nuclides from the canister and a water flow in the open system of the repository 0.42 L/s (13,230 m^3/year), as determined for temperate conditions in the hydrogeological analyses (see above and /Bockgård 2010/). This water is then utilised by humans living at the site (see further next section).

The calculated release rates of radionuclides from a failed canister at the end of the glacial period at year 66,200 AP are shown in Figure 6-17. Only release rates larger than 10^3 Bq/year are displayed. The release rate during the first 1,000 years is dominated by Ni-59, Zr-93 and Nb-94 that are contained in the metal parts of the fuel. When all metal parts are assumed to have been corroded away after 1,000 years, the release rates of Pu-239 and Tc-99 from the spent fuel are the highest. At the time of the start of the second period with glacial conditions at the site, 90,800 years after present, the release rate of Ra-226 has increased to levels comparable with those of Pu-239 and Tc-99.

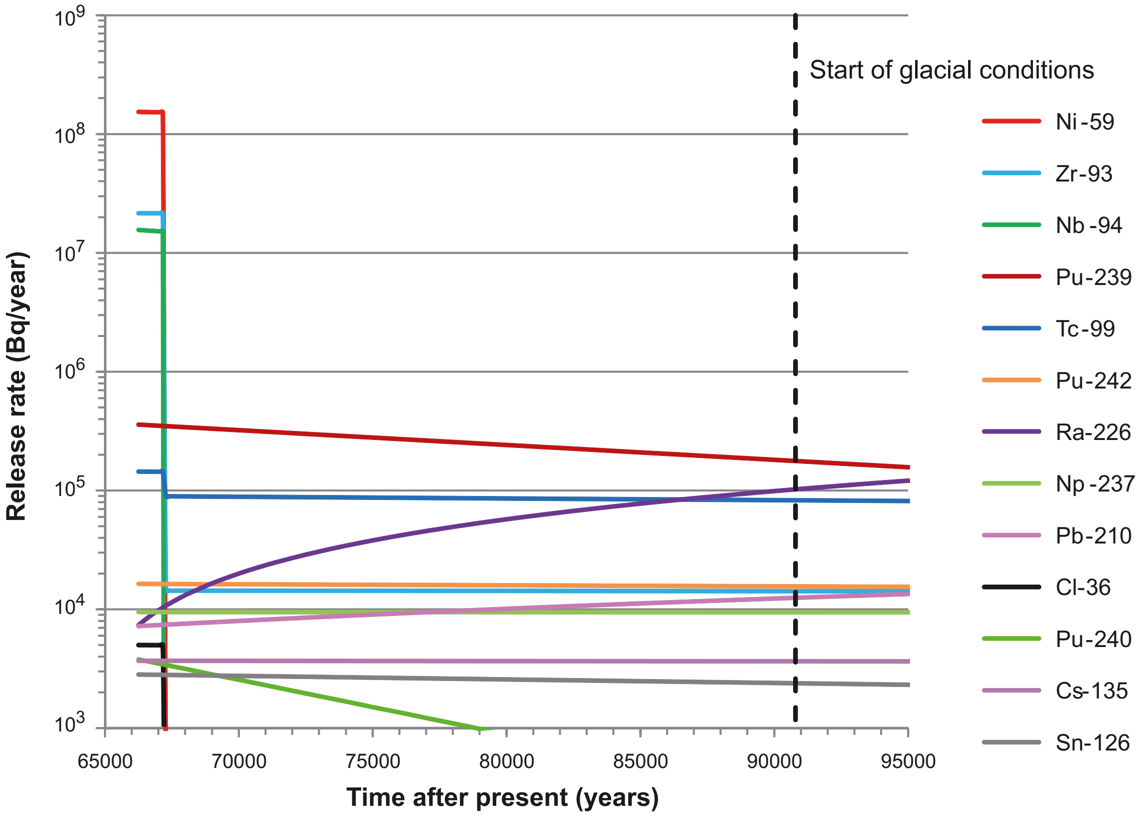


Figure 6-17. *Release rate of radionuclides from one canister failed at the end of the glacial period 66,200 years after present and onwards. The onset of the second period with glacial conditions at the site at year 90,800 AP is marked in the figure.*

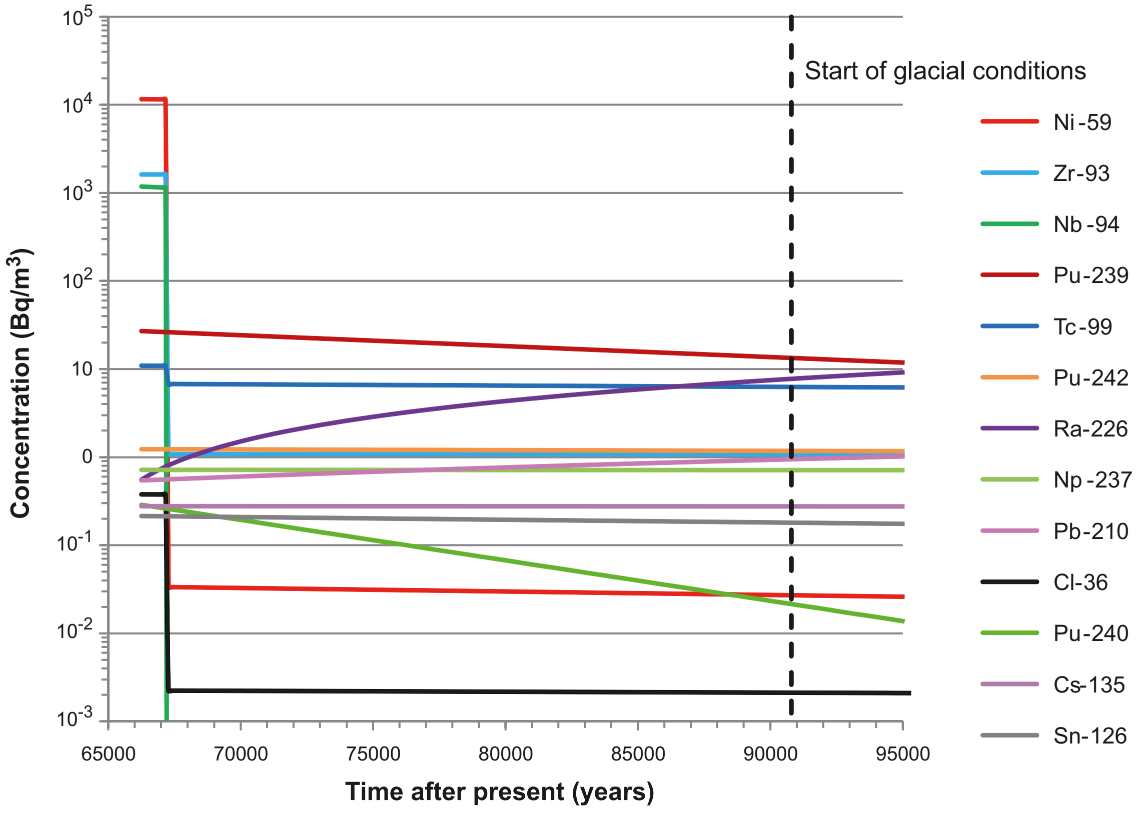


Figure 6-18. *Concentration of radionuclides in the water utilised by humans that arise from the release from one failed canister. The onset of the second period with glacial conditions at year 90,800 AP is marked in the figure.*

Dose consequences

The dose consequences have been estimated using the same radionuclide model for the biosphere as used for other scenarios in SR-Site /Andersson 2010/. It is assumed that the water in the open shafts and ramp above the central area of the repository is used as drinking water for humans and cattle and also as irrigation water for cultivation of vegetables, root crops and cereals. The data used in the calculations are compiled in Table 6-6 and the resulting effective dose as a function of time is provided in Figure 6-19.

Table 6-6. Data used in the calculations of dose consequences from using the water in the open shafts and ramps as drinking water and for irrigation.

Parameter	Value/assumption	Comment/reference
Dose conversion factors	Dose factors for external irradiation, inhalation and ingestion of food cultivated at the site	/Nordén et al. 2010/
Sorption coefficients	Element specific sorption coefficients for soil in the irrigated area	/Nordén et al. 2010/
Dust concentration in the air	$5\ 10^{-8}$kg dry weight/m^3	/Nordén et al. 2010/
Inhalation rate	1 m^3 per hour	/Nordén et al. 2010/
Yearly intake of carbon	110 kg carbon per year	/Nordén et al. 2010/
Yearly intake of water	0.6 m^3/year	/Nordén et al. 2010/
Productivity of vegetables on irrigated land	0.135 kgC per m^2 and year	/Löfgren 2010/
Productivity of root crops on irrigated land	0.127 kgC per m^2 and year	/Löfgren 2010/
Productivity of cereals on irrigated land	0.114 kgC per m^2 and year	/Löfgren 2010/
Density of agricultural soil	323 kg dry weight/m^3	/Löfgren 2010/
Volume of irrigation water used each year	0.15 m^3/(m^2 y)	/Nordén et al. 2010/
Number of irrigation events per year	5	/Nordén et al. 2010/
Runoff	0.186 m/y	/Löfgren 2010/

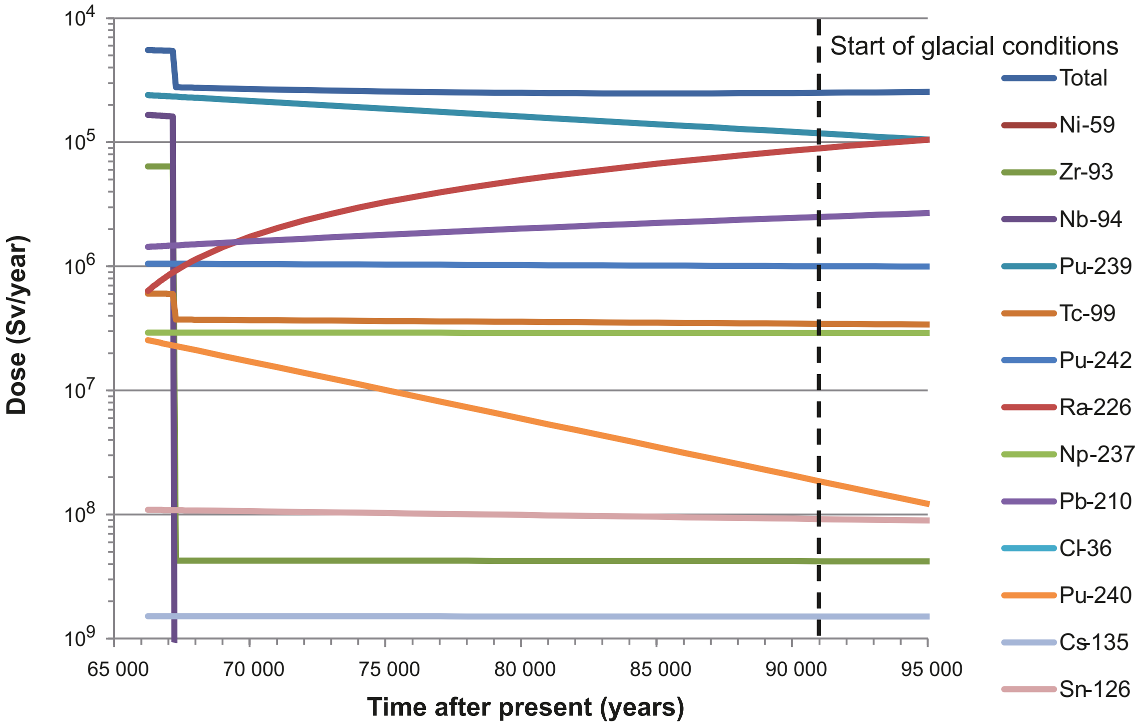


Figure 6-19. *Calculated effective dose from using water in the open shafts and ramp as drinking water and for irrigation.*

The calculated total effective dose during the first 1,000 years after canister failure is 56 µSv/year and the dose is dominated by the intake of food and water contaminated by Pu-239 and by external radiation from Nb-94. Thereafter, the effective dose remains at a fairly constant level of about 25 µSv/year for the remaining period until the start of glacial conditions 90,800 years after present. Over this period, the dose is dominated by the intake of food and water contaminated with Pu-239 and Ra-226.

The calculated effective dose is above the regulatory risk limit of 14 µSv/year during the whole time period analysed, but below the dose of 1 mSv/year from background radiation. The calculated effective dose is obtained for a postulated failure of one canister in the repository during the glacial period prior to 66, 200 years after present. In order to receive an effective dose that is comparable to that received from background radiation, approximately 20 canisters can fail during this period.

6.6.5 Uncertainties

The uncertainties in the analyses of expansion of deposition tunnel backfill are rather large. The friction angle is a function of the swelling pressure and increases with decreasing swelling pressure. The values at low swelling pressure are not well known, but laboratory measurements indicate that the friction angle is higher than 20 degrees at low density and that the lateral stresses (corresponding to the normal stresses towards the rock surface) are higher than the stress in the swelling direction. This means that the resisting force from friction probably is larger than that modelled, which implies that the results probably are pessimistic in the sense that the swelling and thus density loss is smaller than modelled /Åkesson et al. 2010/.

There are a number of uncertainties in the analyses of the impact on groundwater flow of open tunnels in the repository, especially for the simulations with glacial conditions. One important uncertainty relates to the accessibility of water. In reality the flow in an open tunnel below the ice front will probably be limited by the supply of subglacial melt water in the transmissive subglacial layer at the ice-subsurface interface. If the supply of water is insufficient, there will be a drawdown of the pressure and the flow will decrease. In order to give such a high flow as illustrated above, the tunnel entrances have to coincide with a major melt water tunnel under the ice. It should also be noted that the calculations assume a worst case location of the ice front in terms of hydraulic gradient. The hydraulic gradient below the ice sheet when the repository is completely covered by ice may be even lower than during the temperate conditions /Vidstrand et al. 2010/.

Several simplifying assumptions are made in the calculations of oxygen supply to the canister surface. The only transport resistance accounted for is that in the buffer surrounding the canister, whereas transport resistances in the backfill on top of the buffer in the deposition hole and in the deposition tunnel as well as in fractures in the rock are neglected. This is judged as very pessimistic, at least for temperate conditions. Even if the tunnel backfill expands out into the main tunnel and the density of the backfill above a deposition hole is significantly reduced, the transport resistance in the deposition tunnel should still be significant. This is supported by the results of the hydrogeological modelling that indicate that the hydraulic gradients are directed towards the open tunnels in the repository. Any oxygen transport from the open tunnels to the deposition holes then has to take place in a direction opposite to the hydraulic gradient. Other pessimistic assumptions concern the oxygen concentration and that it remains constant over a long time period. There are both biotic and abiotic processes that may consume oxygen in the repository environment.

The assumption that the tunnels will remain open after the advance and retreat of an ice sheet is also uncertain. Although the surface denudation is quite small at Forsmark (Section 4.5.7 in the SR-Site Climate report /SKB 2010i/), it seems very likely that eroded materials will fall down and fill in at least parts of the open tunnels.

The assumption that one canister fail due to corrosion during the next glacial period is not backed-up by any quantitative assessments, but is postulated based on cautious assumptions and therefore associated with large uncertainties. For example, it is assumed that the water flow in a fracture intersecting a deposition hole is large enough to carry away buffer in the deposition hole and backfill material above the deposition hole and to supply enough corrosive species for corrosion breakthrough to occur within an 8,000 year long period. Considering that in the design premises for the final repository there are limits on the water inflow to a deposition hole that will accepted for hosting a canister /SKB 2009b/, the potential for deposition holes that have intersecting fractures with high flow rates should be low.

6.6.6 Conclusions

From the simplified analyses carried out it can be concluded that abandoning the repository without backfilling and sealing all parts of it may imply that backfill in the deposition tunnels is lost and that the safety functions for containment are violated for deposition holes located close to the entrance of the deposition tunnels. Therefore, the general conclusion is that the repository should not be abandoned prior to complete backfilling and sealing.

The analyses of a not completely sealed repository further demonstrate that the repository system adapted to the Forsmark site is robust over a long period of time. Even without backfill in parts of the system, no canister failures are expected as long as diffusion dominates the transport of corrosive species in the backfill in deposition tunnels and buffer in deposition holes. The hydrogeological results for temperate conditions also indicate only small effects of the open tunnels on the Darcy flux at deposition hole positions. Although the open tunnels change the flow paths with somewhat reduced flow related transport resistances in the rock as a result, these resistances are still high. The fact that flow paths are captured by the open tunnels and discharge through the shafts and ramp above the central area is also considered as insignificant, since discharge points occur close to the repository also in the reference evolution and also because periglacial conditions with permafrost in the upper parts of the ramp and shafts will prevail for large parts of the 58,000 year time period. This implies that the impact of the open tunnels for deposition holes other than those directly affected by the expanding tunnel backfill is small.

If corrosion breakthrough in canisters occurs during the next period with glacial conditions, i.e. from 58,000 years to 66,200 years after present according to the reference evolution, the annual effective dose from radionuclides in the failed canisters will exceed the regulatory risk limit. However, as long as the number of failed canisters is limited to less than c. 20, the effective dose from radionuclides in these canisters will be lower than the dose obtained from background radiation. Considering the large uncertainties and cautious assumptions made in the analysis, the calculated annual effective dose should be seen as an illustration of possible consequences rather than an estimation of what the consequence would be if the repository is not completely backfilled and sealed.

7 Conclusions

This report documents the future human actions, FHA, considered in the long-term safety analysis of a KBS-3 repository. Previous chapters provide an account of general considerations concerning FHA, presents the methodology applied in SR-Site to assess FHA and addresses the aspects of FHA that need to be considered in the evaluation of their impact on a deep geological repository. Finally representative scenarios for illustrative consequence analysis are selected and analysed.

In accordance with ICRP recommendations /ICRP 2000/, intrusion in the post-closure phase of institutional control and beyond is primarily prevented through the design of the repository. In addition to that there will presumably continue to be safeguards measures, preservation of information (record keeping) and possibly some sort of markers placed at the site. Based on generally accepted principles and the Swedish Radiation Safety Authority's, SSM's, regulations concerning safety in connection with the disposal of nuclear material and nuclear waste /SSM 2008a/ and on the protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste /SSM 2008b/, the future human actions considered in this part of the safety assessment are restricted to global pollution and actions that:

- are carried out after the sealing of the repository,
- take place at or close to the repository site,
- are unintentional, i.e. are carried out when the location of the repository is unknown, its purpose forgotten or the consequences of the action are unknown,
- impair the safety functions of the repository's barriers.

However, in line with SSM's general guidance /SSM 2008a/, future human actions and their impact on the repository are evaluated separately, and are not included in the main scenario reference evolution or the risk summation.

For the purpose of providing as comprehensive a picture as possible of different human actions that may impact the deep repository as well as their background and purpose, the following systematic approach has been used:

- *Technical analysis:* Identify human actions that may impact the safety functions of the repository and describe and, in technical terms, justify that such actions may occur.
- *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.
- *Choice of representative cases:* The results of the technical and societal analyses are put together and one or several illustrative cases of future human activities are chosen.
- *Scenario description and consequence analysis of the chosen cases.*

The cases "*Canister penetration by drilling*" and "*Rock facility in the vicinity of the repository*" and "*Mine in the vicinity of the Forsmark site*" were selected as representative cases for scenarios related to a sealed repository. According to regulations, it is also necessary to define and analyse a case that illustrates the consequences of an unsealed repository. Since the repository is gradually excavated and operated, the case selected for analysis is representing an *incompletely sealed repository* rather than an unsealed repository. The following is found:

- The dose rate that a member of the drilling personnel would be exposed to while working in the highly contaminated area can be quite high, but if drilling occurs at c 5,000 years after repository closure, the dose rate has decreased to values below background radiation.
- The total dose from using the borehole as a well 300 years after repository closure is below background radiation.

- The maximum total annual effective dose from the use of the contaminated soil for agricultural purposes is very high, but it should be noted that there are a number of simplified, cautious assumptions made in the calculations.
- The impacts of an open borehole on the groundwater flow and on the long-term properties of the backfill in the deposition tunnel in the vicinity of the borehole are assessed as negligible.
- A tunnel constructed in the upper part of the bedrock would not affect the groundwater flow at repository depth such that the presence of the tunnel violates the safety functions of the deep repository.
- Exploitation of the potential mineral resources in the vicinity of the Forsmark site would not impact the safety functions of the repository.
- Abandoning the repository without backfilling and sealing all parts of the repository may imply that backfill in the deposition tunnels are lost and that the safety functions for containment are violated for deposition holes located close to the entrance of the deposition tunnels. If corrosion breakthrough in canisters occurs during the next period with glacial conditions, i.e. from 58,000 years to 66,200 years after present according to the reference evolution, the annual effective dose from radionuclides in the failed canisters will exceed the regulatory risk limit. However, as long as the number of failed canisters is limited to less than c. 20, the effective dose from radionuclides in these canisters will be lower than the dose obtained from background radiation. Considering the large uncertainties and cautious assumptions made in the analysis, the calculated annual effective dose should be seen as an illustration of possible consequences rather than an estimation of what the consequence would be if the repository is not completely backfilled and sealed.

In conclusion, a set of cases illustrating the consequences of Future Human Actions have been identified and the consequences have been assessed in accordance with generally accepted principles and applicable regulations. These cases form the basis for the quantitative assessment of FHA in SR-Site.

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Appendix A

Participants at the workshops

Participants	Organisation etc
Participants at Skebo	
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Ulrik Kautsky	SKB; Biosphere
Lena Morén	SKB; Safety assessments
Carl Johan Nässén	Östhammar Municipality; Reference group
Tom Ritchey	FOA; Defence analysis
Torsten Eng	SKB; Feasibility studies
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Maria Stenström	FOA; Defence analysis
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Lars O Ericsson	SKB; Research and development, Geology
Fred Karlsson	SKB; Research and development, Chemistry
Ulrik Kautsky	SKB; Research and development, Biosphere
Harry Larsson	ROX
Lena Morén	SKB; Research and development, Safety assessments
Jan-Olof Selroos	SKB; Research and development, Safety assessments
Marie Wiborgh	Kemakta
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Lena Morén	SKB; Research and development
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Maria Stenström	FOA; Defence analysis
Hans Weinberger	Ph.D. Royal Institute of Technology, Dept. of History of Science and Technology
Sture Öberg	Professor, Uppsala University, Dept. of Social and Economic Geography

Appendix B

Calculations supporting the assumptions made in the analyses of illustrative cases.

B1 Estimation of the amount of fuel brought to the surface from penetrated canister

Assumptions regarding the amount of spent fuel brought to the surface depend on the canister design. According to the reference design, the canister consists of a tight copper shell and an insert of nodular cast iron containing fuel assemblies /SKB 2010g/. The number of fuel assemblies in one canister is different depending on whether it contains spent fuel from a boiling water reactor, BWR, or a pressurised water reactor, PWR. Canisters for BWR fuel have room for 12 assemblies, whereas canisters for PWR fuel have room for 4 assemblies (see Figure B-1). Each fuel assembly comprise of fuel rods of zirconium alloy tubes, which are stacked with fuel pellets and arranged in square arrays enclosed in a fuel channel (Figure B-2). The BWR fuel assemblies have a cross-sectional area of about 0.140×0.140 m^2 and contain 64 up to 100 fuel rods, whereas the PWR assemblies have a cross-sectional area of about 0.214×0.214 m^2 and contain 204 or 264 fuel rods. The length of the assemblies are 4.4 and 4.1 m for BWR and PWR fuel, respectively /SKB 2010h/.

The drilling angle through the rock is assumed to be 85°, but in the analysis it is simplistically assumed that the drilling through the canister occurs along the axis of the canister. It is further assumed that the drill hits one fuel assembly and that a number of fuel rods in the centre of the hit are brought up to the surface as a drill core and that fuel rods adjacent to the core is crushed during drilling and brought up to the surface as cuttings in the drilling water. The borehole diameter is assumed to be 0.056 m, which is the size of the core-drilled investigation boreholes at Forsmark that produce rock cores with a diameter of 0.051 m. The amount of fuel that is brought to the surface is assumed based on the dimension of the rods and the borehole and drill core diameters and is schematically illustrated in Figure B-3.

Figure B-3 illustrates that on the order of 20 to 22 fuel rods of a total of 100 in a BWR assembly potentially are brought to the surface as cuttings or undamaged. The corresponding number for a PWR assembly is on the order of 26 to 32. These numbers imply that the portion of the fuel in one canister that is brought to the surface is on the order of 2 to 3% (Table B-1). For calculation of the dose consequences it is assumed that 3% of the fuel in a penetrated canister is brought to the surface, mainly as cuttings in the drilling water, but possibly also as a few undamaged fuel rods.

Table B-1. Estimates of the portion of fuel in a penetrated canister that is brought to the surface (data from /SKB 2010g, h/ and Figure B-3).

	BWR	PWR
No of fuel rods per assembly	100	289
No of assemblies per canister	12	4
No of fuel rods per canister	1,200	1,156
No of fuel rods brought to surface	20-22	26-32
Portion of fuel rods brought to surface	0.02	0.02-0.03

B2 Estimation of groundwater flow in deposition holes

Results from the hydrogeological modelling /Joyce et al. 2010/ are used to estimate the magnitude of the water flow in the deposition hole containing the penetrated canister. The volumetric fluxes of water in fractures intersecting deposition holes, Q_f, are calculated from Darcy velocities in fractures intersecting deposition holes in the base case model for temperate conditions at year 2000 AD and the size of the intersecting fractures in the model (File: "fs_Q1_2000_pline_ merged.ptb" in zip file "090827_fs_Q123_2000_pline_merged_ptb" in SR-Site data storage in Subversion). In the results of the hydrogeological modelling, deposition holes that may be excluded due to pre-defined rejection criteria are flagged. These criteria are the full perimeter criterion, FPC, and the extended full perimeter criterion, EFPC. FPC implies that a deposition hole is excluded if its full perimeter is intersected by a fracture that also intersects the full perimeter of the corresponding deposition tunnel. EFPC implies that a deposition hole is excluded if its full perimeter is intersected by a fracture that also intersects the full perimeter of four or more neighbouring deposition holes in the same deposition tunnel.

Figure B-4 shows the frequency histogram and the cumulative distribution function for the volumetric flux in fractures intersecting the deposition holes as calculated from results of the hydrogeological base case model. The upper diagram displays the results when excluding deposition holes that are flagged as they would be excluded if the FPC is applied and the lower diagram the results obtained when excluding deposition holes that are flagged to meet the FPC and/or the EFPC criterion are shown. The statistics for the distributions are given in Table B-2. Based on these results it is assumed that the water flow in the deposition hole with the penetrated canister is 0.1 m^3/year. This value is higher than the 95 percentile of the cumulative distribution and is therefore a rather cautious assumption, since higher flow implies a higher release rate from the fuel of radionuclides that are not solubility limited.

Table B-2. Statistics for the calculated groundwater flow in fractures intersecting deposition holes displayed in Figure B-4.

Case	Water flow in fractures intersecting deposition holes [m^3/year]				
	Min	Max	Average	Median	95 percentile
FPC-flagged holes excluded	$3.6 \cdot 10^{-7}$	16.8	$5.3 \cdot 10^{-2}$	$3.0 \cdot 10^{-4}$	$7.6 \cdot 10^{-2}$
FPC- and EFPC-flagged holes excluded	$3.6 \cdot 10^{-7}$	16.8	$3.6 \cdot 10^{-2}$	$2.1 \cdot 10^{-4}$	$2.0 \cdot 10^{-2}$

B3 Estimation of oxygen supply and canister corrosion

Some simple estimates have been made to set some rough bounds on the time required for canister corrosion breakthrough in the case with an incompletely sealed repository.

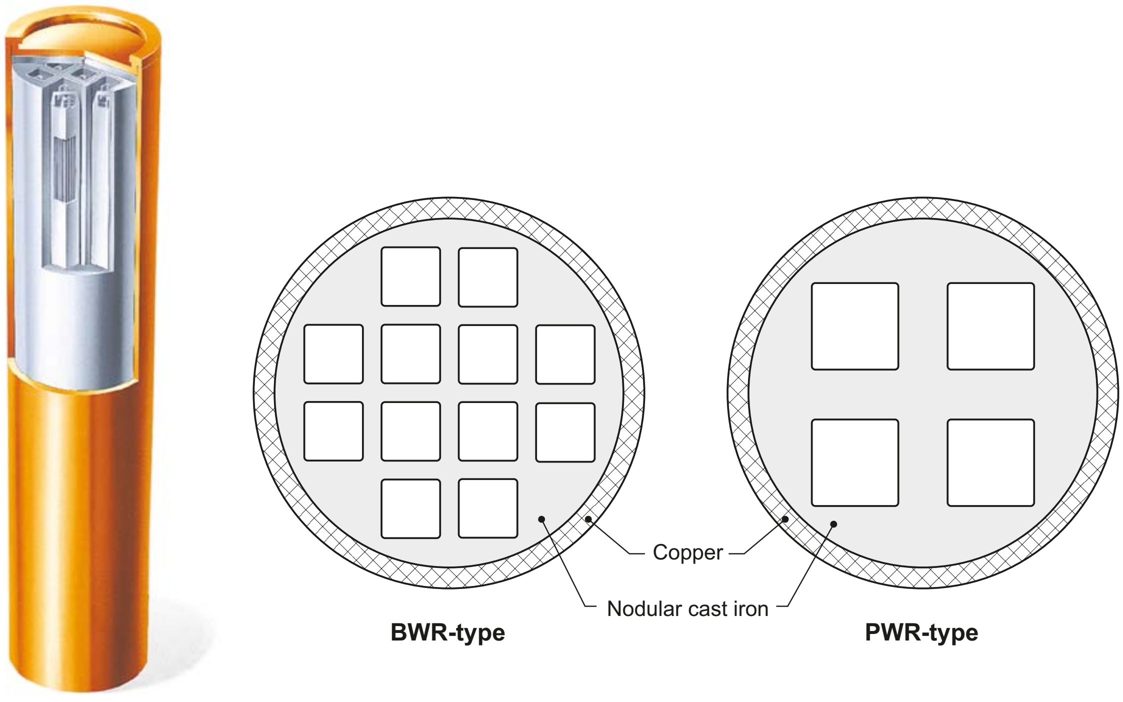
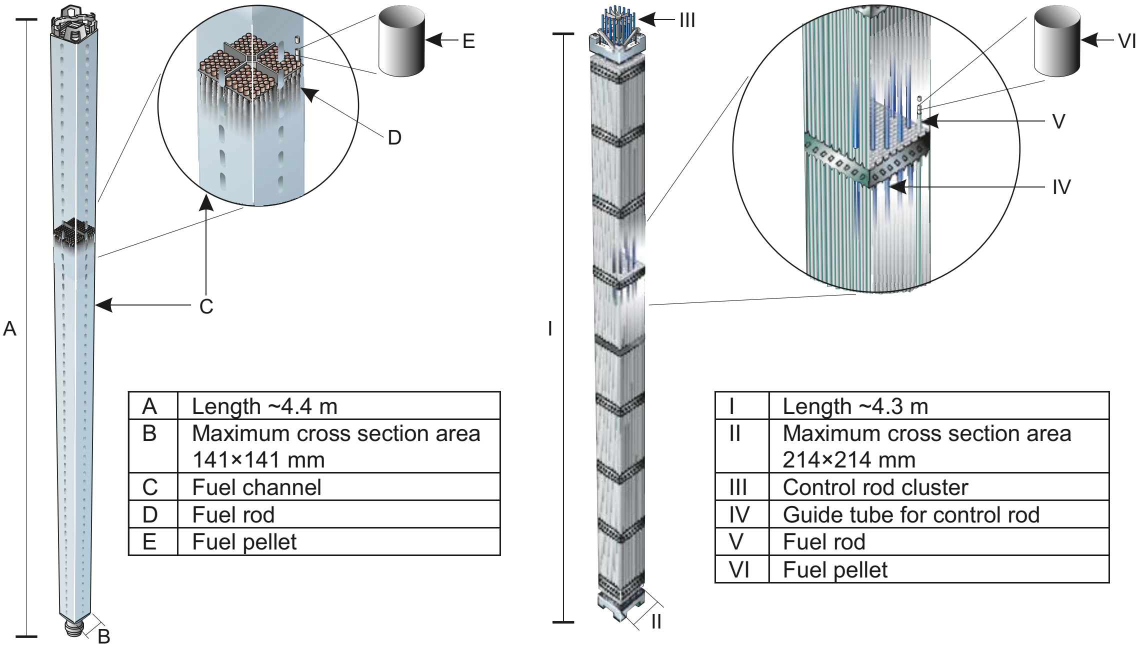


Figure B-1. SKB's reference canister with an outer corrosion barrier of copper and an insert of nodular cast iron with room for 12 (BWR) or 4 (PWR) fuel assemblies (Figures 3-1 and 3-2 in /SKB 2010g/.



A	Length ~4.4 m
B	Maximum cross section area 141×141 mm
C	Fuel channel
D	Fuel rod
E	Fuel pellet

I	Length ~4.3 m
II	Maximum cross section area 214×214 mm
III	Control rod cluster
IV	Guide tube for control rod
V	Fuel rod
VI	Fuel pellet

Figure B-2. *Illustrative BWR (left) and PWR (right) assemblies (Figure 2-5 in /SKB 2010h).*

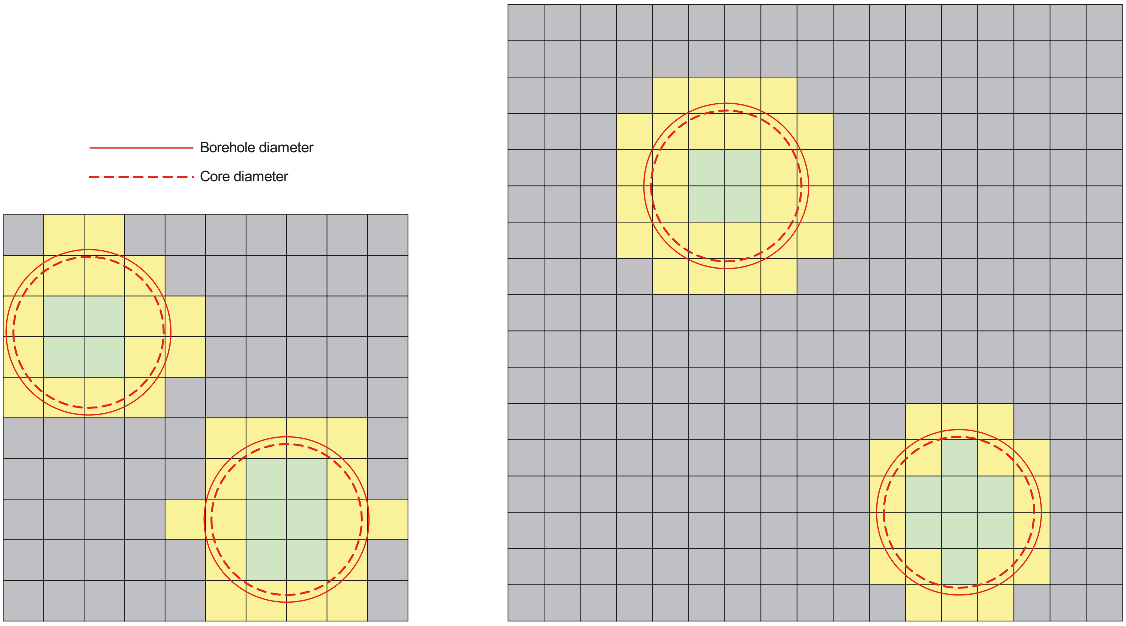


Figure B-3. *A schematic illustration of a BWR fuel assembly with room for 100 fuel rods (left) and a PWR assembly with room for 289 fuel rods and control rods (right). Each grey square symbolise a fuel or control rod. Yellow squares symbolise those potentially crushed by the drilling and brought to the surface as cuttings and green squares those potentially brought to the surface undamaged.*

If only the diffusion resistance in the deposition hole above the canister is considered, the steady-state diffusion flux, F, of a species from the water in the deposition tunnel above the deposition hole to the top of the canister lid can be expressed as:

$$F = \frac{D_e \cdot A\ C}{x} \qquad \text{(Eq. B3-1)}$$

where

D_e is the effective diffusivity of the species (m^2/s)

A is the cross-sectional area through which diffusion takes place (m^2)

C is the concentration of the diffusing species in the water above the deposition hole (mol/m^3)

x is the diffusion distance (m)

According to the buffer production report /SKB 2010f/, the thickness of the bentonite buffer above the canister is 1.5 m, and the diameter of the deposition hole is 1.75 m. Assuming that diffusion takes place over the entire cross-sectional area of the bentonite in a deposition hole, the flux of dissolved oxygen through the buffer above the canister lid has been calculated for two values of the oxygen concentration, 0.3 mol/m^3 as representative for temperate conditions and 1.5 mol/m^3 as representative for glacial conditions /Sidborn et al. 2010/. In addition, two values of the effective diffusivity are applied. As a representative value for diffusion of uncharged species in a bentonite buffer an effective diffusivity of $1 \cdot 10^{-10}$ m^2/s is selected. In order to cover a case where the buffer has lost its swelling properties, a ten times higher effective diffusivity is also explored, which is a value representative of diffusion in unconfined water. Since the diameter of the canister lid is smaller than that of the deposition hole, 1.05 m compared to 1.75 m, calculations have also been made where diffusion through a cross-sectional area of the buffer corresponding to the diameter of the canister is assumed. The resulting supply of oxygen to the canister lid for the different assumptions made is given in Table B-3.

It is further assumed that oxygen reaching the canister lid instantaneously reacts with the copper according to the reaction

$4Cu + O_2 \rightarrow 2Cu_2O$

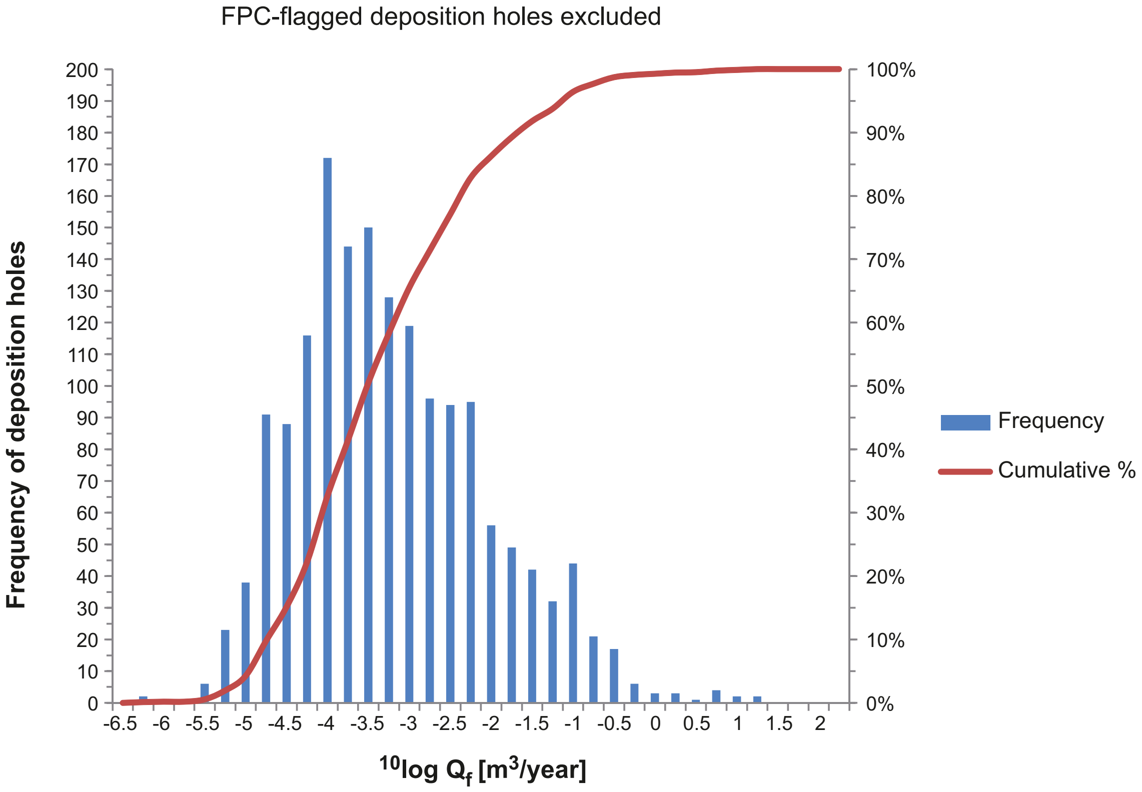
This means that each mole of oxygen will consume 4 moles of copper which equals 254 g copper. From the density of copper (8,920 kg/m^3) and the cross-sectional area of the copper lid (0.87 m^2) the corrosion depth for each mole of oxygen supplied to the lid is 33µm.

The time required for corrosion breakthrough in the 50 mm thick canister lid for the different assumptions made is included in Table B-3. The results indicate that times on the order of 20,000 up to several hundreds of thousands of years are required for corrosion breakthrough in a copper lid to occur.

It should be pointed out that the values provided in Table B-3 are very pessimistic as long as diffusion is the dominating transport mechanism in the backfill in the deposition tunnel. The calculations presume that the groundwater in the deposition tunnel above the deposition hole is saturated with oxygen which is only possible if advective transport of oxygen occurs in the deposition tunnel. As long as diffusion is dominating in the deposition tunnel backfill, it will take considerable time for the build up of an oxygen concentration above the deposition hole to the value assumed in the calculations, if it will ever occur. To exemplify this, the time, t, required for the oxygen concentration in the backfill to reach 5% of the concentration in the groundwater flowing in the open tunnel system has been calculated by the expression /Crank 1975, Figure 4.1/:

$$\frac{D_e \cdot t}{x^2} = 0.1 \qquad \text{(Eq. B3-2)}$$

With an effective diffusivity of $1 \cdot 10^{-10}$ m^2/s, it would take on the order of 13,000 years for the oxygen concentration in the backfill in the deposition tunnel at a distance of 20 m from the intersection with the main tunnel to reach 5% of the concentration in the main tunnel. This distance roughly corresponds to the distance to the first deposition hole in a deposition tunnel. Neglecting any loss of oxygen from the deposition tunnel, Figure 4.1 in /Crank 1975/ indicates that in order to reach c. 50%



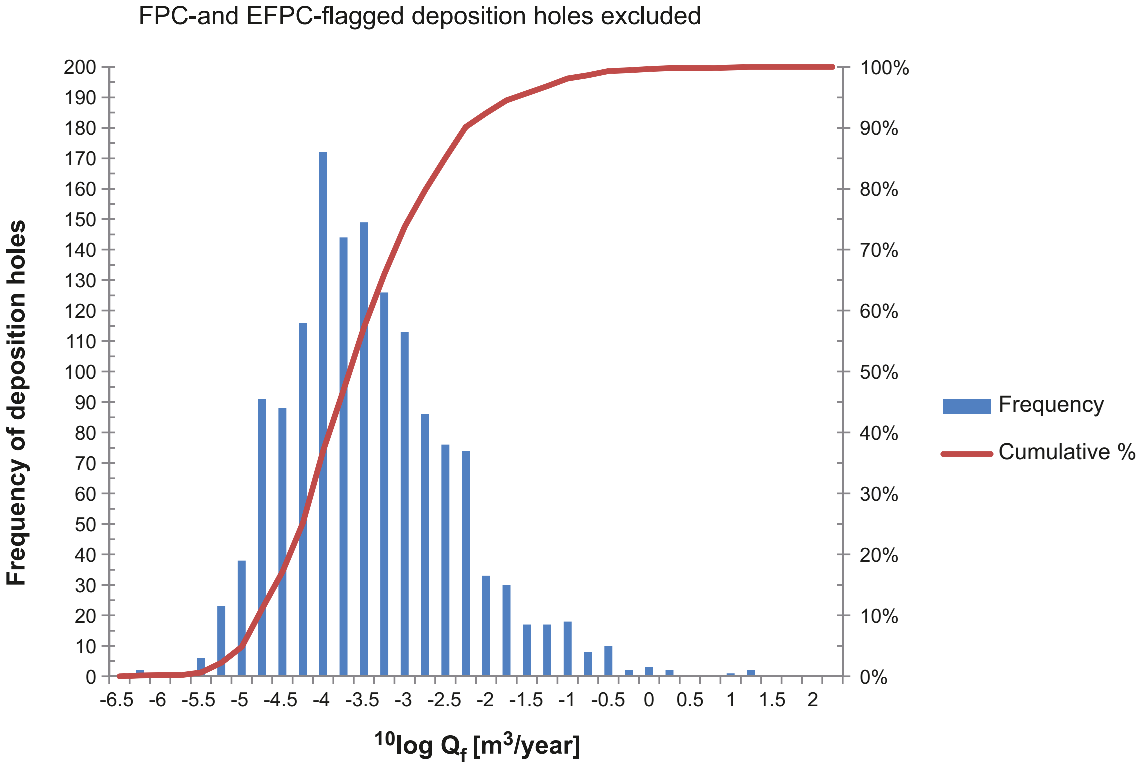


Figure B-4. *Frequency histogram and cumulative distribution function for groundwater flow in fractures intersecting deposition holes in the hydrogeological base case model for temperate conditions at year 2000 AD /Joyce et al. 2010/. Upper diagram; deposition holes that meet the FPC criterion are excluded. Lower diagram; deposition holes that meet the FPC and/or the EFPC criteria are excluded.*

of the concentration in the main tunnel at a distance 20 m into the deposition tunnel, this distance has to be approximately 30% of the distance that the concentration front corresponding to 5% of the concentration in the main tunnel has reached into the deposition tunnel, i.e. this would occur when the 5% concentration front has reached c. 67 m into the deposition tunnel. According to Equation B3-2, this would require on the order of 140,000 years with an effective diffusivity of $1{\cdot}10^{-10}$ m²/s and approximately 14,000 years if a ten times higher effective diffusivity is assumed, e.g. a diffusivity representative of diffusion in unconfined water.

Table B-3. The main assumptions and the calculated supply of oxygen to the canister lid and the time for corrosion breakthrough in the 50 mm thick copper lid.

Case	Oxygen concentration (mol/m³)	Effective diffusivity (m²/s)	Oxygen supply (mol/year)	Time for corrosion breakthrough (years)
Diffusion through cross-sectional area corresponding to the diameter of the deposition hole; A = 2.4 m²	0.3	$1{\cdot}10^{-10}$	$1.5{\cdot}10^{-3}$	$1.0{\cdot}10^{6}$
	0.3	$1{\cdot}10^{-9}$	$1.5{\cdot}10^{-2}$	$1.0{\cdot}10^{5}$
	1.5	$1{\cdot}10^{-10}$	$7.6{\cdot}10^{-3}$	$2.0{\cdot}10^{5}$
	1.5	$1{\cdot}10^{-9}$	$7.6{\cdot}10^{-2}$	$2.0{\cdot}10^{4}$
Diffusion through cross-sectional area corresponding to the diameter of the canister lid; A = 0.87 m²	0.3	$1{\cdot}10^{-10}$	$5.5{\cdot}10^{-4}$	$2.8{\cdot}10^{6}$
	0.3	$1{\cdot}10^{-9}$	$5.5{\cdot}10^{-3}$	$2.8{\cdot}10^{5}$
	1.5	$1{\cdot}10^{-10}$	$2.7{\cdot}10^{-3}$	$5.6{\cdot}10^{5}$
	1.5	$1{\cdot}10^{-9}$	$2.7{\cdot}10^{-2}$	$5.6{\cdot}10^{4}$