Interim storage facility, encapsulation plant and final repository for spent nuclear fuel

# Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation

## Summary of the SR-Can project

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# Summary

## Introduction

This document is the main report from the safety assessment project SR-Can. The SR-Can project is a preparatory stage for the SR-Site assessment, the report that will be used in support of SKB's application for a final repository. The purposes of the safety assessment SR-Can are the following:

1. To make a first assessment of the safety of potential KBS-3 repositories at Forsmark and Laxemar to dispose of canisters as specified in the application for the encapsulation plant.
2. To provide feedback to design development, to SKB's R&D programme, to further site investigations and to future safety assessment projects.
3. To foster a dialogue with the authorities that oversee SKB's activities, i.e. the Swedish Nuclear Power Inspectorate, SKI, and the Swedish Radiation Protection Authority, SSI, regarding interpretation of applicable regulations, as a preparation for the SR-Site project.

The assessment relates to the KBS-3 disposal concept in which copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in saturated, granitic rock, see Figure 1. Preliminary data from the Forsmark and Laxemar sites, presently being investigated by SKB as candidates for a KBS-3 repository are used in the assessment.

An important aim of this report is to demonstrate the proper handling of requirements placed on the safety assessment in applicable regulations. Therefore, regulations issued by the Swedish Nuclear Power Inspectorate (SKIFS 2002:1) and the Swedish Radiation Protection Institute (SSI FS 1998:1) are reproduced in an Appendix where references are given to sections in the main text where the handling of the different requirements is discussed. The principal acceptance criterion requires that "the annual risk of harmful effects after closure does not exceed $10^{-6}$ for a representative individual in the group exposed to the greatest risk". "Harmful effects" refer to cancer and hereditary effects. The risk limit corresponds to an effective dose limit of about $1.4 \cdot 10^{-5}$ Sv/yr. This, in turn, corresponds to around one percent of the effective dose due to natural background radiation in Sweden.

The timeframe for the assessment is one million years after repository closure, in accordance with regulatory requirements. The above risk limit is applicable as a quantitative regulatory limit during approximately the first one hundred thousand years, and thereafter as a basis for discussing the protective capability of the repository, according to SSI.

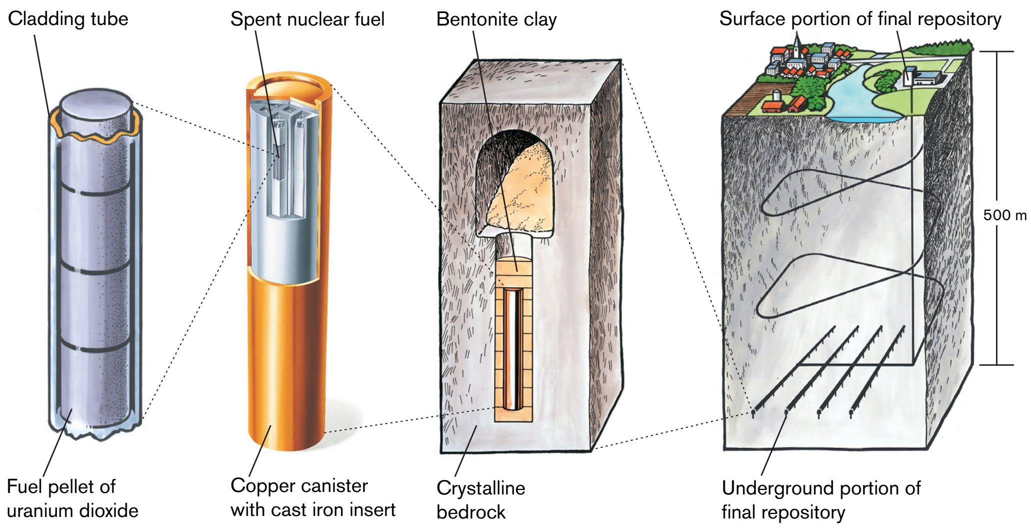


***Figure 1.*** *The KBS-3 concept for disposal of spent nuclear fuel.*

## Methodology

The repository system, broadly defined as the deposited spent nuclear fuel, the engineered barriers surrounding it, the host rock and the biosphere in the proximity of the repository, will evolve over time. Future states of the system will depend on:

- the initial state of the system,
- a number of radiation-related, thermal, hydraulic, mechanical, chemical and biological processes acting internally in the repository system over time and,
- external influences acting on the system.

A methodology in ten steps has been developed for SR-Can, as summarised in Figure 2. The steps are carried out partly concurrently and partly consecutively.

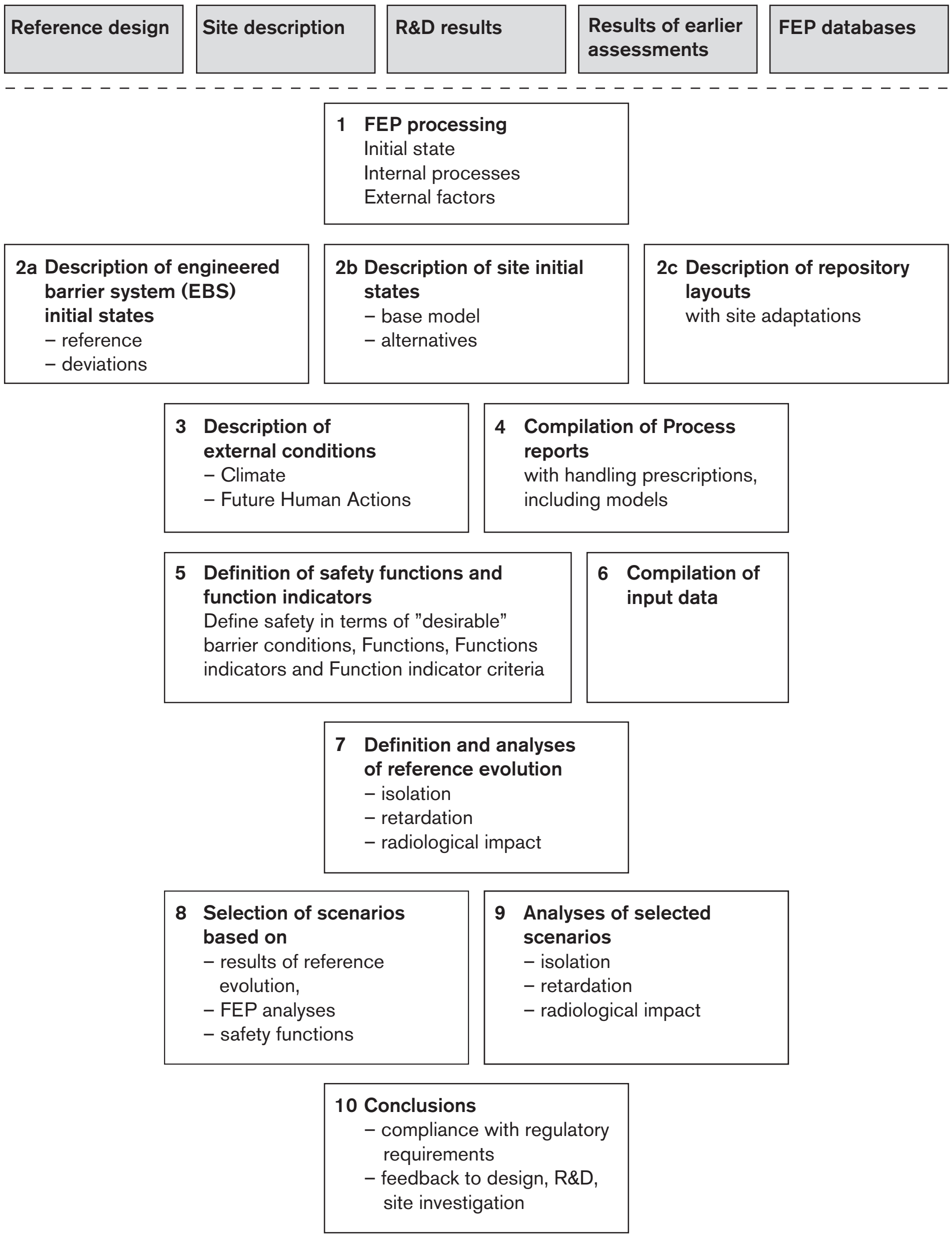


***Figure 2.*** *Outline of the ten main steps of the SR-Can safety assessment. The boxes at the top above the dashed line are inputs to the assessment.*

The ten steps are described in more detail below.

1. Identification of factors to consider (FEP processing)

   This step consists of identifying all the factors that need to be included in the analysis. Experience from earlier safety assessments and KBS-3 specific and international databases of relevant features, events and processes (FEPs) influencing long-term safety are utilised. An SKB FEP database is developed where the great majority of FEPs are classified as being either initial state FEPs, internal processes or external FEPs. Remaining FEPs are either related to assessment methodology in general or determined to be irrelevant for the KBS-3 concept. Based on the results of the FEP processing, an SR-Can FEP catalogue, containing FEPs to be handled in SR-Can, has been established. This step of FEP processing is further described in the SR-Can **FEP report**[1].

2. Description of the initial state

   The initial state of the system is described, based on the design specifications of the KBS-3 repository, a descriptive model of the repository site and a site-specific layout of the repository. The initial state of the fuel and the engineered components is that immediately after deposition as described in the **Initial state report**. The initial state of the geosphere and the biosphere is that of the natural system prior to excavation, as described in the site descriptive models of the Forsmark /SKB 2005c/ and Laxemar /SKB 2006b/ sites. The repository layouts adapted to the sites are provided in underground design reports for each site /Brantberger et al. 2006/ and /Janson et al. 2006/.

3. Description of external conditions

   Factors related to external conditions are handled in the three categories “climate related issues”, “large-scale geological processes and effects” and “future human actions”. The handling of these factors is described in the **Climate report,** the **Geosphere process report**, and the **FHA report**, respectively.

4. Description of processes

   The identification of relevant processes is based on earlier assessments and FEP screening. All identified processes within the system boundary relevant to the long-term evolution of the system are described in dedicated **Process reports**. Short-term geosphere processes/alterations due to repository excavation are also described in these Process reports and are taken into account in the assessment. For each process, its general characteristics, the time frame in which it is important, the other processes to which it is coupled and how the process is handled in the safety assessment are documented.

5. Definition of safety functions, safety function indicators and safety function indicator criteria

   This step consists of an account of the safety functions of the system and of how they can be evaluated by means of a set of safety function indicators that are, in principle, measurable or calculable properties of the system. Criteria for the safety function indicators are provided. The process reports are important references for this step. A FEP chart is developed, showing how FEPs are related to the safety function indicators.

6. Compilation of input data

   Data to be used in the quantification of repository evolution and in dose calculations are selected using a structured procedure. The process of selection and the data values adopted are reported in a dedicated **Data report**. Also, a template for discussion of input data uncertainties has been developed and applied.

7. Definition and analysis of reference evolution

   A reference evolution, providing a description of a plausible evolution of the repository system, is defined and analysed. The isolating potential of the system over time is analysed in a first step, yielding a description of the general system evolution and an evaluation of the safety function indicators. If the evolution indicates breaching of isolation, the retarding potential of the repository and its environs is analysed and dose consequences are calculated for the long-term conditions identified in the first step. Also some canister failure modes not resulting from the reference evolution are analysed in order to further elucidate the retarding properties of the system. Each process is handled in accordance with the plans outlined in the process reports.

[1] The FEP report is one of several principal references in the SR-Can report.

8. Selection of scenarios

   A set of scenarios for the assessment is selected. A comprehensive main scenario is defined in accordance with SKI's regulations SKIFS 2002:1. The main scenario is closely related to the reference evolution analysed in step 7. The selection of additional scenarios is focused on the safety functions of the repository and the safety function indicators defined in step 4 form an important basis for the selection. For each safety function, an assessment is made as to whether any reasonable situation where it is not maintained can be identified. If this is the case, the corresponding scenario is included in the risk evaluation for the repository with the overall risk determined by summation over such scenarios. The set of selected scenarios also includes e.g. scenarios explicitly mentioned in applicable regulations, such as human intrusion scenarios, and scenarios and variants to explore the roles of various components in the repository.

9. Analysis of selected scenarios

   The main scenario is analysed essentially by referring to the reference evolution in step 7. An important result is a calculated risk contribution from the main scenario. The additional scenarios are analysed by focussing on the factors potentially leading to situations in which the safety function in question is not maintained. In most cases, these analyses are carried out by comparison with the evolution for the main scenario, meaning that they only encompass aspects of repository evolution for which the scenario in question differs from the main scenario. For these scenarios, as for the main scenario, a risk contribution is estimated.

10. Conclusions

   This step includes integration of the results from the various scenario analyses, development of conclusions regarding safety in relation to regulatory criteria and feedback concerning design, continued site investigations and SKB's RD&D programme.

# The sites and the repository layouts

## From site data to SR-Can

The information transfer from field investigation to the safety assessment application involves several steps. *Field data* are obtained from various investigation activities, such as air-borne and surface-based geophysics, borehole drilling and borehole testing. The data are quality controlled and then entered into the SKB site characterisation database, Sicada. The field data are interpreted and evaluated into an overall inter-disciplinary *Site Descriptive Model* (SDM), being a synthesis of geology, rock mechanics, thermal properties, hydrogeology, hydrogeochemistry, bedrock transport properties and surface system properties. The SDM is reported in an SDM report. Site data used in SR-Can are assessed in the **Data report**, using the SDM versions 1.2 as input. The data report also describes how non-site specific information were taken into account, adds judgements, based on how the data will be used in SR-Can, on how to handle the uncertainties identified in the SDM and reports the final selections of model input data.

## Forsmark

The Forsmark site is located in northern Uppland within the municipality of Östhammar, about 170 km north of Stockholm. The landscape in Forsmark is a relatively flat bedrock plain that dips gently towards the east. The whole area is located below the highest shoreline that occurred during the last deglaciation. Today's landscape is strongly influenced by the ongoing vertical shore-level uplift of approximately 6 mm per year.

The bedrock in the Forsmark region has been affected by both ductile and brittle deformation. The ductile deformation has resulted in large-scale ductile high-strain zones, but the candidate area is situated within a tectonic lens enclosed between ductile high-strain zones. The bedrock inside the lens is relatively homogeneous, and is dominated by a metagranite with high content of quartz, whereas the lithology and deformation is more complex outside the lens. No potential for metallic and industrial mineral deposits has been recognised within the candidate area. Due to its rather high quartz content, the bedrock is characterised by high thermal conductivity and high mechanical strength compared to typical rock conditions in Sweden.

Three major sets of deformation zones with distinctive orientations have been recognized. In addition to vertical and steeply dipping zones, there are also gently south-east- and south-dipping zones. These gently dipping zones are more frequent in the south-eastern part of the candidate volume and have higher hydraulic transmissivity than vertical and steeply dipping deformation zones at the site. They seem to play an important role in determining the properties of the Forsmark site, such as the distribution of stress, fracturing and the transmissivity distribution of the fractures. The frequency of open and partly open fractures is very low below approximately 300 m depth compared to what is observed in the upper part of the bedrock in the north-western part of the candidate volume, which is the target volume for a potential repository at the site. In addition, the rock stresses are high compared to typical values of the Swedish bedrock, with a potential correlation to the low fracture frequency in this part of the bedrock. The more fractured upper part of the bedrock overlying the target volume is highly transmissive in the horizontal plane and in good hydraulic contact over long distances, whereas at depth the rock appears to have very low permeability with few transmissive fractures. Meteoric water is present in the uppermost approximately 200 m of the bedrock. At depths between 200 and 800 m, the salinity remains fairly constant (5,000–6,000 mg/L) and the water composition indicates remnants of Littorina Sea water. At depths between 800 and 1,000 m, the salinity increases to higher values.

## Laxemar

The Laxemar site is part of the Simpevarp candidate area located in the municipality of Oskarshamn, about 300 km south of Stockholm. The topography is relatively flat. The whole area is located below the highest shoreline associated with the last deglaciation. There is still vertical shore-level uplift of approximately 1 mm per year.

The northern and central parts of the area is dominated by Ävrö granite, whereas in the southern part of the area there are rock domains consisting mainly of quartz monzodiorite and diorite to gabbro forming an arc-shaped body dipping to the north with the concave side to the north. No potential for metallic and industrial mineral deposits has been recognised within the area. Many of the rock types of the Laxemar subarea have low and spatially varying quartz contents. This results in relatively low and varying thermal conductivity, compared to typical values of Swedish bedrock. The mean uniaxial compressive strength is comparatively low in most of the rock types and it also shows a quite large spread. However, these results are based on data from a few samples and are possibly biased by their proximity to a larger deformation zone.

The principal orientations of deformation zones are north-south and east-west. It is judged that most of the local major, steeply dipping zones have been identified at the surface and that gently dipping regional zones do not exist within the local model domain. There remain, however, uncertainties as to the details. There is a high variability in the fracturing and the fracture network description is uncertain. Both measurement data and stress modelling results suggest that the Laxemar subarea can be divided into two different stress domains (I and II), where Stress Domain II has lower stress. The limited data available for the Laxemar 1.2 SDM at the time of the data freeze for this report suggested that the rock volume could be divided into hydraulic domains with different and depth-dependent hydraulic properties. New data available after the data freeze, strongly support these previous indications that there is a depth dependence of hydraulic conductivity and that the rock domains in southern Laxemar have lower conductivities than those in northern Laxemar.

The complex groundwater evolution and patterns at the Laxemar subarea are a result both of the past evolution of groundwater flow and modifications of the groundwater composition caused by microbial processes and water/rock interactions. In the Laxemar subarea, fresh (meteoric) water is found down to 800 m depths, whereas the interface is much shallower at the Simpevarp subarea, which is closer to the sea. Brackish water is found at intermediate depths (500–950 m) and deeper (900–1,200 m) the water becomes saline (6,000–20,000 mg/L Cl, 25–30 g/L TDS). Highly saline water (> 20,000 mg/L Cl, max TDS ~ 70 g/L) has only been found in one borehole at depths larger than 1,200 m.

Although the Laxemar 1.2 SDM is based on a significant amount of data, only a few of these are representative of the potential repository volume(s). This is especially evident for the fracture, thermal and hydraulic data. Data acquired after the data freeze as well as data that will be acquired in the future will allow a more elaborate set of analyses as for Forsmark to be performed also for Laxemar. At this time, it has been decided within the SR-Can team to only carry out a limited set of analyses of the Laxemar site.

### Repository layouts

Preliminary repository layouts, based on the site descriptions, have been developed for the two sites. The layouts relate to a repository for 6,000 canisters. At Forsmark, the reference layout, assessed in SR-Can, is developed for the –400 m level. At Laxemar, the reference layout is developed for the –500 m level.

In order to avoid detrimental impacts from potential future earthquakes, the design applies a respect distance for deformation zones with traces longer than 3 km. For zones with traces shorter than 3 km, a margin for construction, less than 100 m, is applied. A minimum canister separation distance is determined based on the thermal properties. A degree-of-utilisation is estimated by considering mechanical stability, the probability of deposition holes intersecting fractures or deformation zones with radius R > 75 m, and the inflow of water to tunnels and deposition holes using criteria defined in preset design premises. The degree-of-utilisation affects the size of the repository in the layout, i.e. the repository is made large enough to find space for 6,000 accepted canister positions. At Forsmark, the degree-of-utilisation is 89% in the layout and at Laxemar the design is based on a degree-of-utilisation of 80%.

The canister position selection criteria that are applied in the design are preliminary. SR-Can has, therefore, explored the importance of such criteria. The full perimeter intersection criterion (FPC) states that if a fracture is observed over the entire perimeter of the deposition tunnel no deposition hole should be located such that it would be intersected by the assumed extension of that fracture. The evaluation of this criterion has indicated a high efficiency in reducing the number of deposition holes that are intersected by large fractures and at the expense of only a moderate increase in total deposition tunnel length. It is, therefore, assumed in SR-Can that the FPC rule has been implemented in the layouts at the two sites. It is likely that practical criteria concerning flow conditions would relate to results of hydraulic tests, observations of seepage in deposition tunnels or in deposition holes. However, the practicalities or effectiveness of such hydraulic criteria have not yet been assessed by SKB, and SR-Can only makes some initial exploration on the potential importance of flow-related acceptance criteria.

## Safety

The development of the KBS-3 repository concept has been guided by a number of *safety principles*. The long-term performance of the repository can be expressed by studying a set of *safety functions* that should preferably be upheld during the one million year time period covered by the assessment. The safety principles and the implementation of safety functions in SR-Can are summarised below.

### Safety principles

Since work on the Swedish final repository project commenced at the end of the 1970s, SKB has established a number of principles for the design of a final repository. The principles can be said to constitute the safety philosophy behind the KBS-3 concept. They are summarised below.

- By placing the repository at depth in a long-term stable geological environment, the waste is isolated from the human and near-surface environment. This means that the repository is strongly affected neither by societal changes nor by the direct effects of long-term climate change on the ground surface.
- By locating the repository at a site where the host rock can be assumed to be of no economic interest to future generations, the risk of human intrusion is reduced.
- The spent fuel is surrounded by several engineered and natural safety barriers.
- The primary safety function of the barriers is to isolate the fuel.
- Should isolation be breached, the secondary safety function of the barriers is to retard a potential release from the repository.
- Engineered barriers shall be made of naturally occurring materials that are stable in the long term in the repository environment. The long-term properties of the materials shall be verifiable.
- The repository shall be designed and constructed so that temperatures that could have significant detrimental effects on the long-term properties of the barriers are avoided.

- The barriers should be passive, i.e. they should function without human intervention and without artificial supply of matter or energy.

Together with many other considerations, like the geological setting in Sweden and the requirement that the repository must be feasible to construct from a technical point of view, these principles have led to the development of the KBS-3 system for spent nuclear fuel.

### Safety functions

The key safety related features of the KBS-3 disposal system can be summarised in the safety functions isolation and retardation.

A detailed and quantitative understanding and evaluation of repository safety requires a full description of how the main safety functions of isolation and retardation are achieved by the components of the repository. Based on the understanding of the properties of the components and the long-term evolution of the system, a number of subordinate safety functions to isolation and retardation can be identified. The following definitions are used:

- A safety function is a role through which a repository component contributes to safety.
- A safety function indicator is a measurable or calculable property of a repository component that indicates the extent to which a safety function is fulfilled.
- A safety function indicator criterion is a quantitative limit such that if the safety function indicator to which it relates fulfils the criterion, the corresponding safety function is maintained.

An overview of the safety functions, their indicators and the indicator criteria is given in Figure 3.

Safety functions aid in the evaluation of safety, but the fulfilment of all safety function indicator criteria is neither necessary nor sufficient to argue safety. The different safety function indicator criteria are furthermore determined with varying margins to acceptable performance.

Safety functions are related to, but not the same as, design criteria. Whereas the latter relate to the initial state of the repository and primarily to its engineered components, the former should be fulfilled throughout the assessment period and relate, in addition to the engineered components, to the natural system.

## Reference evolution of the repository

A reference evolution of KBS-3 repositories at the Forsmark and Laxemar sites over the entire one million year assessment period is studied to gain an understanding of the overall evolution of the system as a basis for scenario selection and scenario analyses. The aim is to describe a reasonable evolution of the repository system over time.

Two variants of the reference evolution are analysed:

- A base variant where the external conditions during the first 120,000 year glacial cycle are assumed to be similar to those experienced during the last cycle, the Weichselian. Thereafter, seven repetitions of that cycle are assumed to cover the entire one million year assessment period.
- A greenhouse variant in which the future climate and, hence, external conditions are assumed to be substantially influenced by antropogenic greenhouse gas emissions.

The analysis is carried out in four time frames and in each frame the safety functions mentioned above are evaluated.

### The excavation/operation phase

The analyses for the excavation and operation phases of the repository, expected to last several decades, mainly focus on disturbances of the mechanical, hydrological and chemical conditions induced by the excavation/operational activities. Issues of potential importance to long term safety include:

- The creation of an excavation damaged zone (EDZ) around deposition holes and in particular deposition tunnels, impairing the retention properties of the rock, relating to the safety functions R2a and R2b in Figure 3.

- The potential for the buffer to experience piping, i.e. the formation of hydraulically conductive channels, immediately after deposition, due to the high groundwater pressure gradients in the open repository. This, in turn, may lead to erosion of the deposited buffer, caused by water flowing in the pipes. This relates to the safety function Bu1 in Figure 3.

### The initial temperate period

This period is expected to last several thousand years. The host rock and back-filled tunnels are expected to be re-saturated and the subsequent evolution in the geosphere is characterised by a return to the natural, undisturbed situation prior to excavation. The analysis of this period includes comprehensive thermal, hydrogeological, mechanical and chemical modelling.

An important safety relevant issue with long-term consequences is the occurrence of spalling of the rock around the deposition holes, induced by additional stresses from the thermal load of the deposited waste. This relates to the safety functions R2a and R2b in Figure 3.

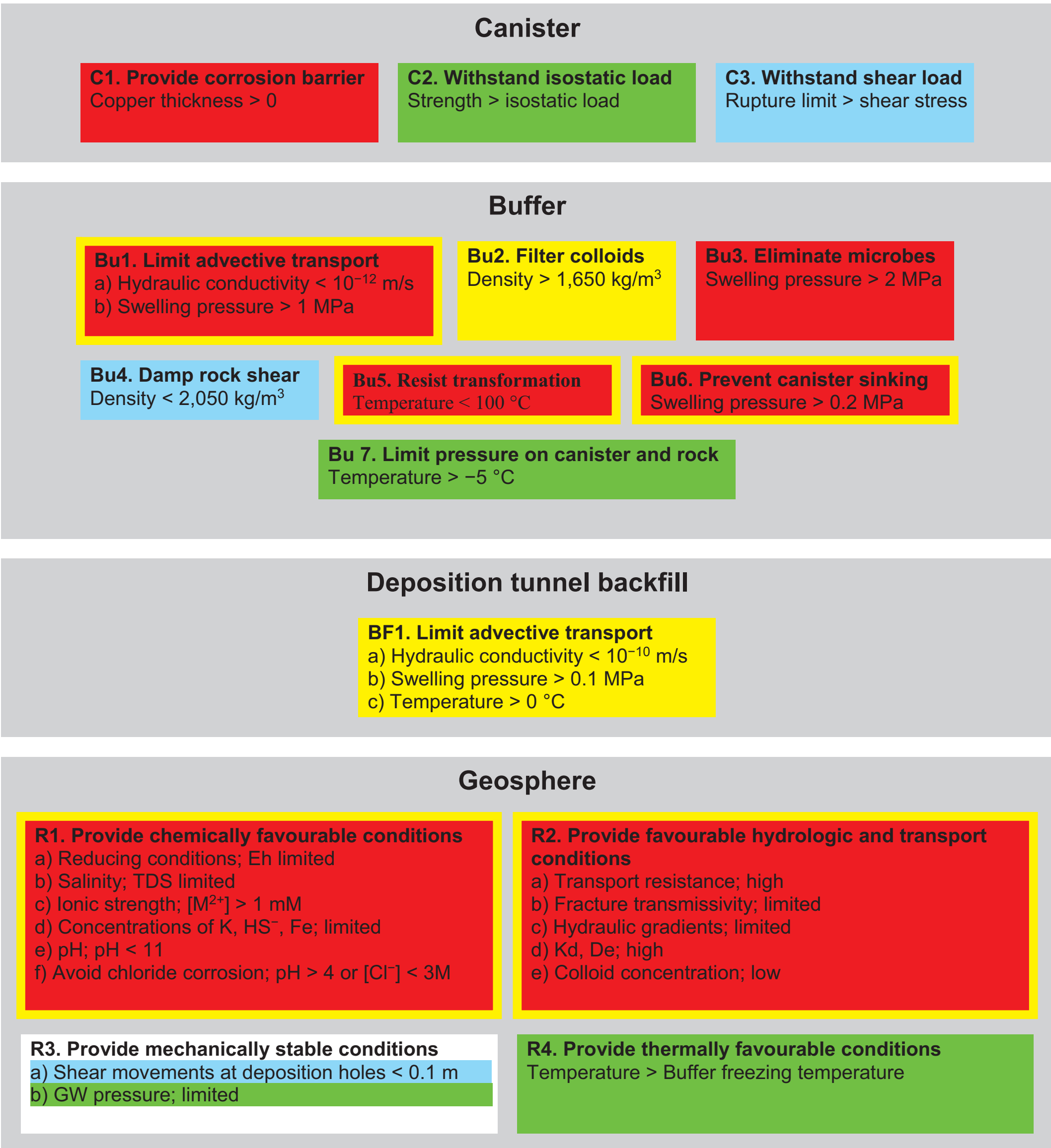


***Figure 3.*** *Safety functions (bold), safety function indicators and safety function indicator criteria. When quantitative criteria cannot be given, terms like "high", "low" and "limited" are used to indicate favourable values of the safety function indicators. The colour coding shows how the functions contribute to the canister safety functions C1 (red), C2 (green), C3 (blue) or to retardation (yellow). Many functions contribute to both C1 and retardation (red box with yellow board).*

The evolution during the initial temperate period does not imply that any other safety functions are jeopardised.

## The first glacial cycle

The occurrence of permafrost and glacial conditions, exemplified by a model reconstruction of the last glacial cycle, called the Weichselian and comprising the Weichselian glacial and the Holocene interglacial, implies major alterations on the ground surface and also of some of the bedrock conditions of importance for repository safety. These include:

- The development of permafrost.
- Altered mechanical loads on the bedrock from an overlying ice sheet, leading to altered rock stresses and potentially the occurrence of large earthquakes.
- Increased hydrostatic pressures at repository depth for glacial conditions.
- The occurrence of dilute groundwaters during glacial conditions potentially causing erosion of buffer and backfill through colloid-formation that, in turn, would lead to enhanced canister corrosion.
- The possible penetration of oxygen to repository depth for short periods of increased groundwater flow during glacial conditions.
- Factors affecting retardation in the geosphere, such as temporarily increased groundwater flows.

The results of the analyses imply the following.

- Large earthquakes, of magnitude 6 or larger, in the vicinity of the repository are highly unlikely but cannot be completely ruled out. The results of the probabilistic calculations imply that the mean number of canister failures during the initial glacial cycle due to such events is 0.014 and 0.0077 for the Forsmark and Laxemar sites, respectively. This relates to safety functions C3 and R3a in Figure 3.
- Dilute groundwaters may occur for extended periods of time when glacial conditions prevail. This may lead to loss of buffer mass in some deposition holes, to the extent that advective conditions are created. This leads to enhanced canister corrosion, but no canisters are assessed to fail during the initial glacial cycle. This relates mainly to the safety functions C1, Bu1 and R1c in Figure 3.

Other aspects of the evolution during the first glacial cycle are assessed not to threaten any of the safety functions of the repository.

## The time after the first glacial cycle up to one million years

The continued evolution of the repository system is analysed by assuming another seven repetitions of the 120,000 year Weichselian glacial cycle.

The same phenomena as for the initial glacial cycle could impair safety for the repeated glacial cycles:

- The likelihood of large earthquakes is assessed to increase with time. The mean number of canister failures for the entire one million year assessment period is calculated to 0.12 for Forsmark and to 0.065 for Laxemar.
- The extent of loss of buffer mass due to erosion is expected to increase with time. The resulting enhanced canister corrosion may lead to failures of a few canisters during the one million year assessment period. The result is sensitive to a number of factors analysed in the reference evolution.

The results of the analysis do not implicate threats to any additional safety functions.

## The greenhouse variant

In the greenhouse variant, it is assumed that a temperate climate prevails for 50,000 years before the relatively mild onset of the base variant of the next glacial cycle, as opposed to a few thousand years of initial temperate conditions without an increased greenhouse effect. Throughout the report it is implicitly understood that the greenhouse variant describes a situation with an increased greenhouse effect.

As seen above, the processes that are potentially the most detrimental to repository safety are related to glacial conditions. Therefore, a prolonged period of temperate climate is essentially beneficial for safety.

### Radiological consequences

Radionuclide transport and dose calculations are carried out for four canister failure modes. Two of these, failure due to corrosion and due to shear movements, were identified in the reference evolution. Two additional failure modes are analysed to further illustrate retardation, the secondary safety function of the repository.

A comprehensive set of calculation cases are carried out to analyse retardation and to elucidate the impact of a number of uncertain factors identified in the reference evolution. In the biosphere, radionuclide transport and dose consequences are estimated using a novel approach based on site specific biosphere data and taking the temporal development of the landscape into account.

The results imply that the canister failures potentially resulting from *the reference evolution* yield consequences that are well below the regulatory risk limit.

## Scenarios

The further assessment of repository safety is broken down into a number of scenarios. A comprehensive main scenario represents a reasonable evolution of the repository system. The evolution of this scenario is closely linked to the reference evolution. A set of additional scenarios are defined in order to cover uncertainties not addressed in the reference evolution, e.g. more extreme climate conditions than those obtained from the reconstruction of the Weichselian glacial cycle in the reference evolution.

The safety functions are used to obtain a comprehensive set of additional scenarios, focussing on issues of relevance to repository safety. When defining a scenario, a violation of a safety function is *postulated* and all conceivable routes to such a violation are then scrutinised. The aim is to answer the question: Is there any reasonable way in which this scenario could occur? If this is found to be the case, the consequences of the scenario in question are included in a risk summation for the repository. If not, the scenario is considered as “residual”, and consequences may be analysed for illustrative purposes.

A scenario addressing canister failure due to isostatic over-pressure exemplifies the approach. In this scenario, mishaps in the manufacturing of the load bearing canister insert, higher than reference buffer swelling pressures and very large ice sheets yielding high groundwater pressures are considered.

In addition to the so derived scenarios, scenarios required by regulations or otherwise identified as relevant for the assessment are also sought, resulting in a selection of several scenarios related to future human actions. These are residual scenarios, i.e. they are not included in the risk assessment for the repository. Table 1 gives an overview of the selected scenarios.

The selected scenarios are analysed, often as extensions of the analyses of the reference evolution. Two failure modes of the canister were found to contribute to risk:

- Failure due to copper corrosion when advective conditions prevail in the deposition hole as a result of buffer erosion. The buffer erosion is caused by colloid formation due to glacial melt waters of low ionic strength. This failure occurs in the reference evolution and hence in the main scenario. In the canister corrosion scenario, which is analysed to cover uncertainties not addressed in the reference evolution, larger consequences than for the reference evolution are predicted.
- Failure due to rock shear movements caused by large earthquakes. This failure mode has a low probability, but cannot be entirely ruled out.

**Table 1. Result of scenario selection. Green cells denote conditions for the base variant of the main scenario, red cells denote deviations from these conditions. EBS stands for engineered barrier system, i.e. the canister, the buffer and the deposition tunnel.**

| Main scenario | | | | |
|---|---|---|---|---|
| **Name** | **Initial state EBS** | **Initial state Site** | **Process handling** | **Handling of external conditions** |
| Base variant | Reference ± tolerances | Site descriptive model version 1.2 (with variants/ uncertainties) | According to Process Reports | Reference climate (repetitions of Weichselian glacial cycle) No future human actions (FHA) |
| Greenhouse variant | Reference ± tolerances | Site descriptive model version 1.2 (with variants/ uncertainties) | According to Process Reports | Extended warm period No future human actions (FHA) |
| **Additional scenarios based on potential loss of safety functions (“less probable” or “residual” based on outcome of analysis)** | | | | |
| **Name** | **Initial state EBS** | **Initial state Site** | **Process handling** | **Handling of external conditions** |
| Buffer advection | Scrutinise uncertainties of relevant initial state factors, internal processes and external conditions possibly leading to violation of safety function indicator under consideration. Analysis of main scenario used as starting point. | | | |
| Buffer freezing | See above | | | |
| Buffer transformation | See above | | | |
| | Consider each of above three buffer states + intact buffer when analysing below three canister scenarios. | | | |
| Canister failure due to isostatic load | Scrutinise uncertainties of relevant initial state factors, internal processes and external conditions possibly leading to violation of safety function indicator under consideration. Analysis of main scenario used as starting point. | | | |
| Canister failure due to shear movement | See above | | | |
| Canister failure due to corrosion | See above | | | |
| **Scenarios related to future human actions** | | | | |
| **Name** | **Initial state EBS** | **Initial state Site** | **Process handling** | **Handling of external conditions** |
| Boring intrusion | As base variant of main scenario | As base variant of main scenario | As base variant of main scenario, except processes affected by boring | Reference climate + boring |
| Additional intrusion cases, e.g. nearby rock facility | As base variant of main scenario | As base variant of main scenario | As base variant of main scenario, except processes affected by intrusion | Reference climate + intrusion activity |
| Unsealed repository (not analysed in SR-Can) | As base variant of main scenario, but insufficient sealing | As base variant of main scenario | As base variant of main scenario, modified according to initial state | Reference climate |

## Main results and conclusions

The most important findings in the SR-Can project are summarised in subsections A, B and C below. A more detailed discussion on compliance with the regulatory risk limit is given in subsection D and additional results and conclusions are summarised in subsection E.

### A. Compliance with the regulatory risk criterion

#### *No canisters are assessed to fail during the initial temperate period, expected to last several thousand years*

No canister failures are expected for either of the sites during the initial temperate period after deposition, estimated to last several thousand years. Furthermore, the evaluations of the canister sealing procedure undertaken so far, have led to the conclusion that all canisters will be tight at deposition.

#### *A repository at Forsmark is assessed to comply with the regulatory risk criterion*

The preliminary analyses carried out in SR-Can suggest that a KBS-3 repository at Forsmark will comply with the regulatory risk criterion issued by SSI.

Uncertainties in the hydrogeological interpretation and understanding of the Forsmark site are, however, considerable and, when propagated to various parts of the analyses, lead to a wide range of conclusions regarding e.g. buffer colloid release and water flow properties. A reduction of these uncertainties would allow more definite conclusions in future assessments. Even the most pessimistic interpretation of the Forsmark site is, however, assessed to comply with the regulatory risk criterion.

#### *A repository at Laxemar is preliminarily assessed to comply with the regulatory risk criterion – but more representative data is required*

The Laxemar site descriptive model version 1.2 is not sufficiently representative of the potential repository volume to allow definite conclusions regarding compliance. In particular, the hydraulic interpretation of the site is based on data partly obtained outside the candidate volume for the repository. Furthermore, recently obtained data indicate more favourable hydraulic properties than those on which the site model used in SR-Can is based.

However, it is noted that with the data used for Laxemar, the site is assessed to comply with the risk criterion and that use of more recent data would likely strengthen this conclusion.

### B. Issues related to glacial conditions

In general, the most severe impact on the repository will occur during future glacial conditions. A number of conclusions regarding effects of such conditions can be drawn.

#### *Freezing of an intact buffer is assessed as ruled out – even for very pessimistically chosen climate conditions*

Freezing of an intact buffer is assessed as ruled out for both sites, even for the most pessimistic climate conditions considered. For a water-filled cavity in an eroded buffer, freezing is not entirely ruled out for the most pessimistically chosen climate development at Forsmark, but calculations demonstrate that the mechanical pressure on the canister is acceptable in such cases.

#### *Canister failure due to isostatic load is assessed as ruled out – even for very pessimistically chosen climate conditions*

Canister failure due to isostatic load is assessed as ruled out for both sites, also for the most severe future glacial conditions considered.

### *Oxygen penetration is preliminarily assessed as ruled out – even for very pessimistically chosen conditions*

Oxygen penetration to repository depth for enhanced groundwater flows under an ice sheet, jeopardising the favourable reducing chemical conditions, is assessed as ruled out, based on the analyses carried out in SR-Can. This result is in agreement with conclusions from several earlier assessments. The modelling example is, however, stylised and simplified, meaning that additional analyses are warranted to increase confidence in the results. Such studies will be undertaken in SR-Site.

### *The risk contribution from earthquakes is assessed as small*

Canister failures due to post-glacial earthquakes cannot be completely ruled out. The risk contribution from this failure mode is, however, small. The probabilistic analyses made imply that, on average, it would take considerably more than one million years for even one such canister failure to occur.

### *Loss of buffer may occur from exposure to glacial melt waters but the extent is uncertain – further studies are required*

Substantial loss of buffer through buffer erosion/colloid release may occur as a result of intrusion of low ionic strength glacial melt waters in a 100,000 year perspective. The knowledge of the processes involved is uncertain and further research is being undertaken as a matter of priority. A status report will be given in SKB's RD&D programme 2007 to be published in 2007.

### *Substantial loss of buffer may lead to canister failures in very long time perspectives*

Loss of buffer mass, to the extent that advective conditions prevail in the buffer, which cannot be ruled out in a 100,000 year perspective, will lead to enhanced canister corrosion rates. In a one million year perspective, this may lead to failures of some tens of canisters for the pessimistic hydraulic interpretation of the Forsmark site, with cautious assumptions regarding sulphide concentrations and cautious assumptions regarding deposition hole acceptance rules.

### *A prolonged period of warm climate (increased greenhouse effect) before the next glacial period is assessed as primarily beneficial for repository safety*

Since the processes that are potentially the most detrimental to repository safety are related to glacial conditions, a prolonged period of temperate climate is deemed as beneficial for safety. This concerns in particular the two main contributions to the calculated risk in SR-Can, namely i) potential buffer erosion with subsequent enhanced canister corrosion as a result of intrusion of glacial melt waters and ii) the occurrence of large earthquakes during deglaciation. Further evaluations of the geochemical evolution for a prolonged warm period are required in order to better substantiate the conclusion that the geochemical conditions would remain beneficial.

## C. Other issues related to barrier performance and design

### *Crucial to avoid deposition positions intersected by large or highly water conductive fractures – further studies are required*

The main risk contributors in SR-Can are related to the occurrence of large and/or highly transmissive fractures intersecting deposition holes. This applies to the buffer colloid release process and the impact of major earthquakes in the vicinity of the repository. These two phenomena are related to canister failures due to canister corrosion and to secondary rock shear movements, respectively. As also the retention in a large, highly transmissive fracture is small, such failures are in general associated with high consequences. Such fractures will be avoided when identified. The likelihood of occurrence of such fractures and the probability of unsuitable deposition holes remaining unidentified are, in many respects, uncertain and the results of the analysis are sensitive to these uncertainties. It is important to establish well-founded acceptance criteria for deposition holes as a basis for future assessments. This needs to be studied both by simulation of the effects of applying potential criteria and by exploring the practicability of applying the criteria.

*The heat from the canister may fracture the rock in the deposition hole wall, which may enhance the in- and outward transport of dissolved substances – further studies are required*

Thermally induced spalling around deposition holes may have a considerable impact on mass exchange between the flowing groundwater and the buffer as long as diffusion is the dominant transport mechanism in the buffer. If advective conditions prevail in the buffer, the effects of spalling are much less pronounced because it adds little to the already increased flow rate. There are uncertainties regarding the extent and the consequences of spalling and further studies are ongoing.

*The importance of the backfilled deposition tunnels as a transport path for radionuclides is limited*

The importance of the backfilled deposition tunnel as a transport path for radionuclides is limited in comparison with fractures intersecting a deposition hole. Also, deterioration of the deposition tunnel backfill material has limited consequences in terms of radionuclide releases from the near field.

*The importance of the excavation damaged zone in the rock around the deposition tunnels as a transport path for radionuclides is limited*

The importance of the excavation damaged zone (EDZ) around deposition tunnels is limited in comparison to other transport routes for radionuclides, even for very pessimistic assumptions about the EDZ in relation to the reference excavation method.

Cautious excavation methods are still recommended for the deposition tunnels, because competing transport routes may be assessed as less important with additional data and because the conclusion regarding the EDZ is based on simplified, stylised modelling.

## D. Calculated individual risks

The calculated individual risks for repositories at Forsmark and Laxemar are presented in Figure 4. Note that temperate conditions are assumed for the biosphere, whereas it is expected that the sites will be submerged or covered by ice during a considerable part of the one million year assessment time, yielding negligible risks for these periods. Also, several pessimistic assumptions have been made in order to not underestimate the risk.

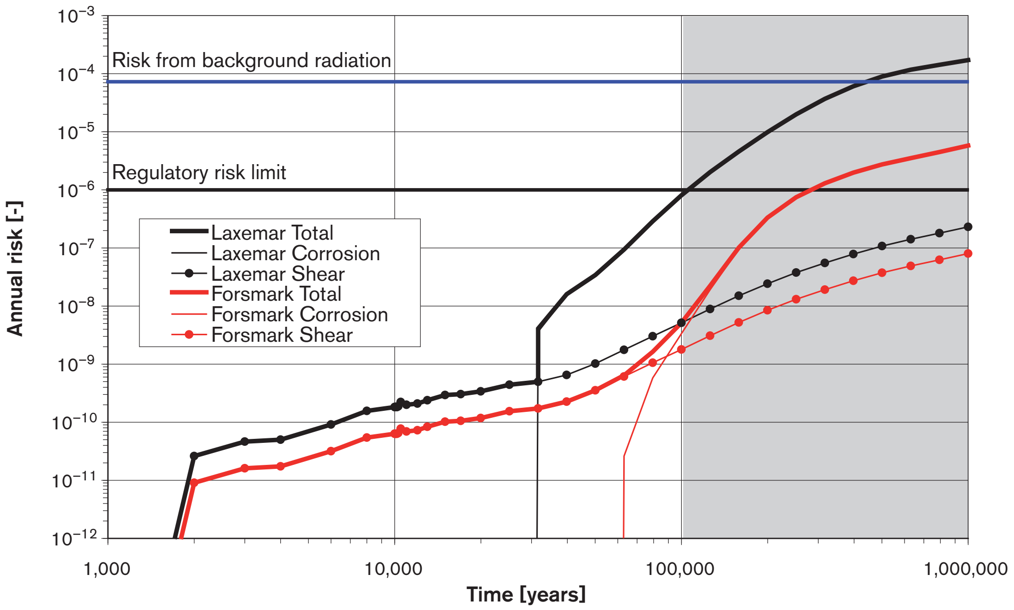


***Figure 4.*** *Risk summation for the two sites. Temperate conditions are assumed for the biosphere, whereas it is expected that the sites will be submerged or covered by ice during a considerable part of the one million year assessment period, yielding negligible doses. Several other uncertainties are handled pessimistically.*

### *Compliance for the initial glacial cycle*

For the initial glacial cycle, two risk contributions are identified: That from earthquakes and that from canister failures due to corrosion if the buffer has been eroded by glacial melt waters.

The probability of canister failures due to earthquakes for this period is very small and this probability is included in the risk estimate.

As concerns failures due to corrosion, a few canisters are calculated to fail during the initial glacial cycle at both sites. The total calculated risk up to 100,000 years is at most, i.e. after 100,000 years, close to the regulatory risk limit at Laxemar and about two orders of magnitude below at Forsmark. The risk is pessimistically based on that calculated for the canister corrosion scenario, where several uncertainties are handled pessimistically, due to insufficient understanding of groundwater flow and composition for glacial conditions and of the response of the buffer to glacial groundwaters. The risk calculated for Forsmark is based on a pessimistic interpretation of the current hydraulic situation. As also pointed out previously, the representativity of the Laxemar hydrogeological model is questionable. More recent site data from the candidate repository area indicate that the hydrogeological conditions are more favourable than those adopted in the model used in SR-Can. This would reduce the risk contribution from canister failures due to corrosion.

It is, thus, concluded that the calculated risks for the two sites comply with the regulatory requirements during the initial glacial cycle after closure.

### *Repository performance for the time beyond the initial glacial cycle*

The same canister failure modes as for the initial glacial cycle contribute to individual risk during the period after the initial glacial cycle up to one million years after closure.

For Forsmark, the calculated risk contribution from earthquakes is more than one order of magnitude below the regulatory limit throughout the assessment period, whereas the contribution from corrosion failures is above the regulatory limit at the end of the one million year period.

For Laxemar, the contribution from earthquakes is similar to that for Forsmark, whereas that from corrosion failures exceeds the risk limit by about two orders of magnitude at the end of the assessment period.

As stated in SSI's general guidance, "*a strict quantitative comparison of calculated risk in relation to the criterion for individual risk in the regulations is not meaningful*" for this time period. Rather, the results are used as a basis for discussing how pessimistically handled uncertainties can be reduced and how the protective capability of the repository can be improved as suggested by the general guidance.

It is important to note that the calculated risks, although exceeding the risk limit applicable for the initial 100,000 years, are considerably less than those due to the background radiation throughout the assessment period for Forsmark. For Laxemar, they are well below the background radiation for several hundred thousand years and become comparable to the background radiation only at the end of the one million year assessment period. Furthermore, as for the initial glacial cycle, a number of issues have been treated pessimistically and further knowledge may lead to a substantial reduction of these risk estimates in future assessments.

It is, thus, concluded that calculated risks for the time beyond the initial glacial cycle fulfil the regulatory requirements for this time period.

## E. Additional results and conclusions

A number of additional results have been obtained on which conclusions are drawn from the SR-Can assessment:

- A first evaluation of effects on the environment from release of radionuclides has been made. Most radionuclides fall below screening limits, meaning that no additional analyses are required. A few nuclides in the most pessimistic calculation cases exceed the screening limits at the end of the assessment period, requiring more detailed assessments.
- Two alternative safety indicators have been used as a complement to the risk indicator; release constraints issued by the Finnish regulator STUK and contents of naturally occurring radionuclides in the environment at the repository sites.

- A first account is made of the aspects of Best Available Technique, BAT, that can be addressed based on the results of the safety assessment.
- A number of bounding cases, assuming fictitious complete loss of one or several barrier functions have been analysed. The results indicate that the calculated doses are below the natural background radiation also for very severe losses of safety functions. For example, an initial total loss of the canister and buffer in all deposition holes yields, for a repository at the Forsmark site, doses that are comparable to those caused by the background radiation. The bounding analyses demonstrate the multi-barrier character of the KBS-3 system.
- A set of design basis cases have been derived. These are to be used as one of several inputs to substantiate the design basis for the repository which includes the establishment of requirements on barrier properties.
- Detailed feedback is provided to canister design and fabrication, to repository design, to further site investigations and site modelling, to SKB's RD&D programme and to the next safety assessment, SR-Site.

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