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Project Alternative Systems Study – PASS. Analysis of performance and long-term safety of repository concepts

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Kemakta Konslut AB

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PROJECT ALTERNATIVE SYSTEMS STUDY - PASS.
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PROJECT ALTERNATIVE SYSTEMS STUDY - PASS

Analysis of Performance and Long-term Safety of Repository Concepts

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ABSTRACT (ENGLISH)

This study is a part of the Project on Alternative Systems study, PASS, with the overall aim to perform a technical/economical ranking of alternative repository concepts and canisters for the final storage of spent nuclear fuel. The comparison should in the first stage separately assess Technology in construction and operation, long-term Performance and Safety, and Costs.

Three of the repository concepts are assumed to be located at a depth of approximately 500 m in the host rock, KBS-3, Very Long Holes (VLH) and Medium Long Holes (MLH). In the KBS-3 concept the canisters are deposited in vertical deposition holes in a system of parallel storage tunnels. In the VLH concept larger canisters are deposited in long horizontal tunnels. The MLH concept, is an evolution of the two other concepts, with KBS–3 type canisters deposited in horizontal tunnels. Smaller canisters are to be deposited in deep bore holes at a depth between 2000 to 4000 m in the Very Deep Holes (VDH) concept. In all concepts the canisters will be surrounded by a bentonite buffer.

The aim of the present study is to analyze and compare the performance and long-term safety of the repository concepts. Only a qualitative comparison of the concepts is made as no calculations of radionuclide releases or dose to man have been performed. The ranking of the repository concepts is based on differences in the performance of various mechanisms for isolation or retention as well as on the performance of the integrated repository barrier system. To evaluate and compare the performance of the repository systems a set of comparison criteria has been used. The comparison considers uncertainties associated with the estimates of doses, the importance of individual mechanisms and processes for the overall performance, the possibilities to validate and demonstrate the long-term performance and the sensitivity to rare events.

The ranking of the repository concepts was carried out by comparing the VDH, VLH and MLH concept with the KBS-3 concept. The performance and long-term safety of the repositories located at 500 m level will be based on a multiple barrier system and the predictions for the concepts will involve similar uncertainties. The differences that have been identified in the performance of the barriers are not distinguishing any of the concepts as more favourable than the others with respect to overall safety. The conclusion is also that all the 500 m level alternatives can be expected to comply with strict requirements concerning the long-term safety. The performance and long-term safety of the VDH concept is determined by the function of only one individual barrier and does not fulfill the multiple barrier principle in the same way as the other concepts.

ABSTRACT (SWEDISH)

Denna studie är en del av ett större projekt PASS-studien, med målsättningen att studera och jämföra alternativa förvarssystem och kapslar för djupförvaring av använt kärnbränsle. Jämförelsen baseras i ett första steg på tekniska faktorer avseende byggande och drift, långsiktig funktion och säkerhet samt kostnader.

Tre av förvarssystemen är lokaliserade på 500 m djup i berggrunden, KBS-3, långa tunnlar (VLH) och medellånga tunnlar (MLH). I KBS-3 konceptet placeras kapslarna en och en i vertikalt borrade hål i ett system av parallella deponeringstunnlar. I VLH konceptet placeras större kapslar i centrum av långa fullortsborrade tunnlar. I MLH konceptet placeras kapslar av samma typ som för KBS-3 i horisontella tunnlar. I VDH konceptet deponeras små kapslar i borrade hål på ett djup av 2000 till 4000 m. I alla koncepten omges kapslarna av en bentonitbuffert.

Målsättningen med denna studie är att analysera och jämföra långsiktig funktion och säkerhet för de olika koncepten. Jämförelsen är endast kvalitativ eftersom inga beräkningar av nuklidfrigörelse med dospåverkan har genomförts. Rangordningen av förvarskoncepten är baserad på skillnader i enskilda barriärers funktion samt funktionen av det integrerade förvarssystemet. Jämförelsekriteria har definierats för utvärderingen och jämförelsen av förvarssystemen. I jämförelsen beaktas osäkerheter, möjligheter till validering och demonstration av långsiktig funktion samt förvarsystemens känslighet för extrema händelser.

Rankningen av förvarskoncepten har genomförts genom att jämföra VDH, VLH och MLH koncepten med KBS-3 konceptet. Den långsiktiga funktionen och säkerheten för förvarskoncepten lokaliserade på 500 m nivå i berggrunden baseras på flerbarriärprincipen och i utvärderingen av koncepten ingår likvärdiga osäkerheter. De skillnader som identifierats mellan enskilda barriärers funktion är inte tillräckliga för att säga att något av alternativen är bättre än det andra vad avser långsiktig funktion och säkerhet. Slutsatsen blir att alla förvaren på 500 m nivå kan förväntas uppfylla kraven på långsiktig säkerhet. Långsiktiga funktionen och säkerheten hos VDH konceptet är i huvudsak endast beroende av barriärerna i den omgivande berggrunden. Säkerheten för VDH konceptet baseras således på färre barriärer än de andra koncepten.

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APPENDICES

1. INTRODUCTION

1.1 Background

In Sweden high level waste is planned to be disposed of in a final repository in crystalline host rock. The Swedish Nuclear Fuel and Waste Management Co, SKB, is presently considering several alternatives for repository design and canister design for the spent nuclear fuel from the operation of the nuclear power reactors.

In the KBS-3 concept the canisters are deposited in vertical deposition holes in a system of parallel storage tunnels and in the Very Long Holes (VLH) concept larger canisters are deposited in long horizontal tunnels. The repositories are assumed to be located at a depth of approximately 500 m. In the Very Deep Holes (VDH) concept smaller canisters are assumed to be deposited vertically in deep drilled bore holes at a depth between 2000 to 4000 m. In all the alternatives the canisters are assumed to be surrounded by a bentonite buffer.

During this project a combination of the KBS-3 and VLH concepts, the Medium Long Holes (MLH) concept, has been developed. In the MLH concept canisters very similar to the KBS-3 type are to be surrounded by bentonite and emplaced in horizontal tunnels.

This study is a part of PASS (Project on Alternative Systems Study), with the overall aim to perform a technical/economical ranking of the alternative repository concepts and the different canister alternatives presently considered. The comparison should at the first stage assess both Technology in construction and operation, long-term Performance and Safety, and Cost aspects separately.

1.2 Aim of present study

The aim of the present study is to analyze and compare the performance and long-term safety of the repository concepts within the PASS. The methodology used for the comparison must ensure that all information forming the basis for the comparison is presented in a systematic way. In a later stage it must be possible to review the outcome of the study and also to reevaluate the comparison with respect to other aspects to be considered or new findings in studied areas. Therefore, this study includes a compilation of basic assumptions and descriptions of the expected performance of the different repository systems.

1.3 Outline of present report

An overview of the steps involved in the ranking procedure chosen for the comparison of the performance and the long-term safety of the repository concepts is given in Figure 1-1.

Firstly, all background material forming the basis for the performance and comparison of the alternative concepts in this study is presented.

Information available on geological and geochemical conditions in the host rock at depths relevant for the four repository concepts is given in Chapter 2 and in more detail in Appendix 6.

A general description of the repository concepts (KBS-3, VLH, MLH and VDH) and the canister designs considered in this study is presented in Chapter 3. Here also the assumed properties of near-field barriers, near-field rock, disturbed by the existence and the excavation of the repository, and far-field rock are presented.

The expected performance of the individual repository barriers in short- and long-term perspectives and their importance for the radionuclide release is presented in Chapter 4.

A comparison of the performance of individual barriers and the repository barrier system with respect to long-term safety is presented in Chapter 5.

Finally, in Chapter 6 the ranking of the repository concepts with respect to long-term safety is addressed.

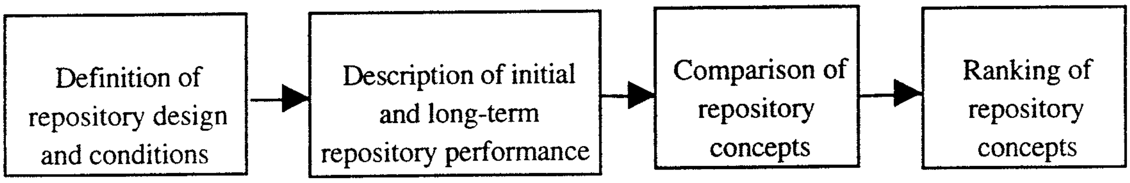

Figure 1-1. Ranking procedure for the long-term safety of repository concepts.

2. GEOLOGY

2.1 General

This chapter includes a short compilation of geological and geochemical conditions at depths relevant for the alternative repository concepts. The repository is proposed to be located at the 500 m level for the KBS-3, VLH and MLH concepts, while the canisters in the VDH concept will be located at the 2000-4000 m level. A more complete description of the geological and geochemical conditions is presented in Appendix 6.

2.2 Geological conditions, variation with depth

The variation in hydraulic conductivity with depth has been studied at some of the KBS-3 sites. i.e. the sites that were investigated for the KBS-3 safety assessment, down to depths of about 700 m. The overall trend is that the hydraulic conductivity for local fracture zones as well as for the rock mass decreases with increasing depth.

The hydraulic conductivity generally decreases rapidly the first 200-300 m in local fracture zones as well as in the rock mass. The hydraulic conductivity at 500 m depth is about 10^{-9} m/s for the local fracture zones and about 10^{-10} m/s in the rock mass.

The temperature increases with increasing depth. For the SKB 91 study [*SKB, 1992*] the measurements from Finnsjön were used as input data. In these investigations the temperature gradient was found to be 1.3 °C/100 m. The absolute temperature at the 500 m level was found to be 12.3 °C.

2.3 Geochemical conditions, variation with depth

There are a number of investigation of the variation in groundwater composition with depth [*Ahlbom et al., 1989 and Laaksoharju, 1990a, b*] covering depths from the surface down to about 800 meters. A compilation of measurements concerning groundwater composition at different depth is given in Appendix 6.

2.4 Host rock description at 500 m level

A description of a reference site regarding geological and hydraulic characteristics is needed to compare the different concepts . This description for the 500 m level is based on the significant amounts of geological information that have been collected from measurements in Fjällveden, Gideå, Kamlunge, Sternö, Finnsjön, Stripa and SFR [*Ahlbom, 1991, Pusch et al. 1991*]. The sites consist of either granite or gneiss.

This compilation is mainly based on work by Ahlbom [*1991*] and Pusch et al. [*1991*]. Both these works are based on essentially the same information obtained from sites studied within the SKB-program, but have different ambitions and differ somewhat in estimated hydraulic conductivities for the discontinuities. The description regarding larger discontinuities, fracture zones, are quite similar concerning frequency and widths, but the hydraulic conductivities are estimated to be about one order of magnitude higher in the study by Pusch et al. which is based on more general background data whereas the compilation by Ahlbom is limited to the sites mentioned above.

The observed fracture zones have been classified into different orders dependent on their characteristics [*Ahlbom, 1991*]:

Regional fracture zones	(1st order)
Local fracture zones	(2nd order)
Minor intrablock fracture zones	(3rd order)
Subhorizontal fracture zones	(orders unknown)

An estimate of the distance between fracture zones for a given order is dependent on dominating fracture zone directions. The spacings in Table 2–1 have therefore been estimated for two directions: perpendicular and parallel to the dominating set of fracture zones. Table 2–2 gives the characteristics for rock at 500 m depth that are used in this study.

Table 2–1. Estimated average hydraulic conductivities at 500 m depth for different orders of fracture zones and the surrounding rock mass.

Discontinuity	Hydraulic conductivity [m/s] Ahlbom/Pusch et al.
Regional fracture zones (1st order)	$10^{-7}/10^{-6}$
Local fracture zones (2nd order)	$10^{-8}/10^{-7}$
Minor intrablock fracture zones (3rd order)	$10^{-9}/10^{-8}$
Fractures (4th order)	$10^{-11}/10^{-11}$
Subhorizontal fracture zone	10^{-7}/-
Surrounding rock mass	10^{-11}/-

Table 2–2. Rock characteristics at the 500 m level to be used in this study.

Discontinuity	Spacing perpendicular/parallel [m]	Width [m]	Hydraulic conductivity [m/s]
1st order	3200/6900	50-150	10^{-7}
2nd order	400/800	1-20	10^{-8}
3rd order	50-100	0.5-2	10^{-9}
4th order	0.4/0.8	0.01	10^{-11}
Subhorizontal fracture zones	700	*	10^{-7}

*Not possible to assess

2.5 Host rock description for VDH

Rock at depths ranging from 2000 to 4000 m is significantly less investigated than rock at the 500 m level. The compilation given in Appendix 6 is based on the study by Juhlin and Sandstedt [*1989*]. The geological model for Swedish crystalline rock at great depths is mainly based on the results from the Gravberg-1 borehole within the Siljan Ring area.

A review of geoscientific data available from other deep boreholes in crystalline rock confirms in principle the geological model based on the Gravberg-1 borehole. The following is proposed for crystalline rock:

- Below 500-200 m the average hydraulic conductivity if the rock is orders of magnitude lower than that of the rock above.

- The deep rock features have likely more or less stagnant fluid systems with higher salinities than the upper part of the bedrock.

3. DESCRIPTION OF CONSIDERED REPOSITORY CONCEPTS

3.1 General

Several alternative repository concepts for the disposal of spent fuel are presently considered. In all concepts the spent fuel is to be disposed of in canisters surrounded by a clay barrier in the host rock. In this chapter a description of the alternative repository concepts and the basic assumptions going into this study are presented.

The repository designs are based on the disposal of approximately 7 900 metric tonnes of spent fuel, 6 100 tonnes from BWR units and 1 800 tonnes from PWR units. This amount corresponds to the spent fuel produced by twelve nuclear reactors in operation until the year 2010. Activated metal parts, other long-lived waste and some LLW and ILW are foreseen to be disposed of in a separate repository adjacent to the repository for spent fuel, but this repository is not considered here.

In the study the spent fuel has been assumed to be a BWR-fuel with a burnup of 38 GWd per tonne of uranium.

3.2 Reference concept - KBS-3

In the KBS-3 concept the canisters are deposited in individual vertical deposition holes in the bottom of horizontal storage tunnels at a depth of 500 m in the host rock. A schematic presentation of the repository layout is given in Figure 3–1.

3.2.1 Repository design

The canisters are emplaced in deposition holes with a depth of 7.6 m and a diameter of 1.6 m in the bottom of the storage tunnels and surrounded by compacted bentonite. The spacing between the individual deposition holes is on average 6 m The repository will be constructed with a minimum respect distance of 100 m from the deposition holes to the nearest known zone with high water flow or zone with limited rock stability [*KBS-3, 1983*].

In PASS [*PASS, 1991*] a composite canister (ACP) is considered as an alternative to the lead-filled copper canister. The dimensions of the ACP canister is somewhat larger and the number of BWR fuel assemblies has been increased from 8 to 12. The dimensions of the deposition hole has been assumed to increase accordingly giving the measures mentioned above. In order not to exceed a temperature of 100 °C in the bentonite buffer the respect distance between the storage tunnels is increased to 35 m. The reference amount of spent fuel, 7 900 tonnes, corresponds to about 3 800 canisters. The total length of storage tunnels required to host the canisters is equal to about 25 km and the repository area has been assumed to be less than 1 km^2.

The access to the repository is in PASS assumed to be by ramp in all repository concepts at the 500 m level (not shown in Figure 3-1).

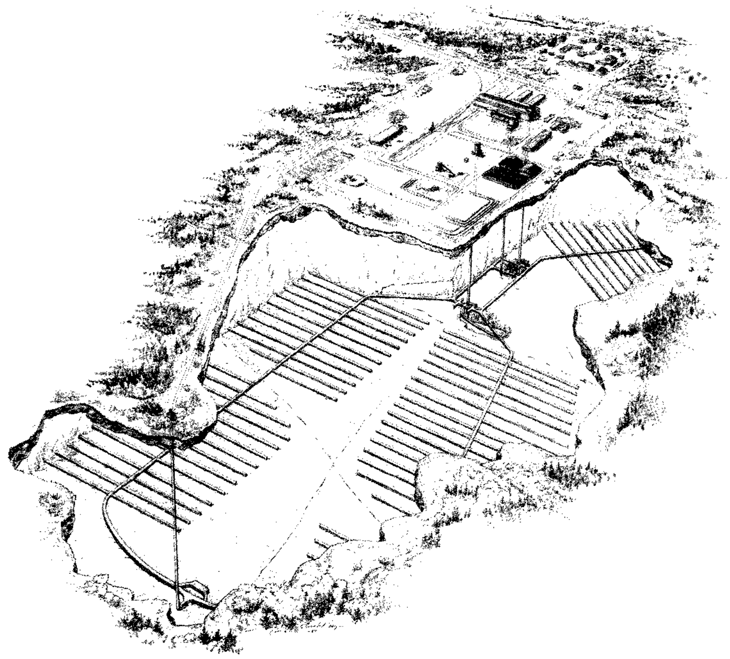

Figure 3-1. Artists view of a KBS-3 repository.

3.2.2 Canister alternative

Different canister and filling materials are being studied. In the KBS–3 study a lead-filled copper canister and a HIP (Hot Isostatic Pressing) copper canister were the main alternatives whereas the lead-filled copper canister was chosen in SKB 91 [SKB, 1992]. Both are cylinders with an outer diameter of about 0.8 m.

In PASS copper-steel canister (Advanced Cold Process, ACP), hosting 12 spent fuel assemblies of the BWR-type, has been assumed as reference canister. The ACP canister consists of a 50 mm thick inner steel canister giving the support and an outer 50 mm thick layer of copper. The 1.2 m^3 void inside the canister is not filled giving this canister a weight of only about 14 tonnes including the fuel assemblies. The top of the canister has to be welded, see Figure 3–2.

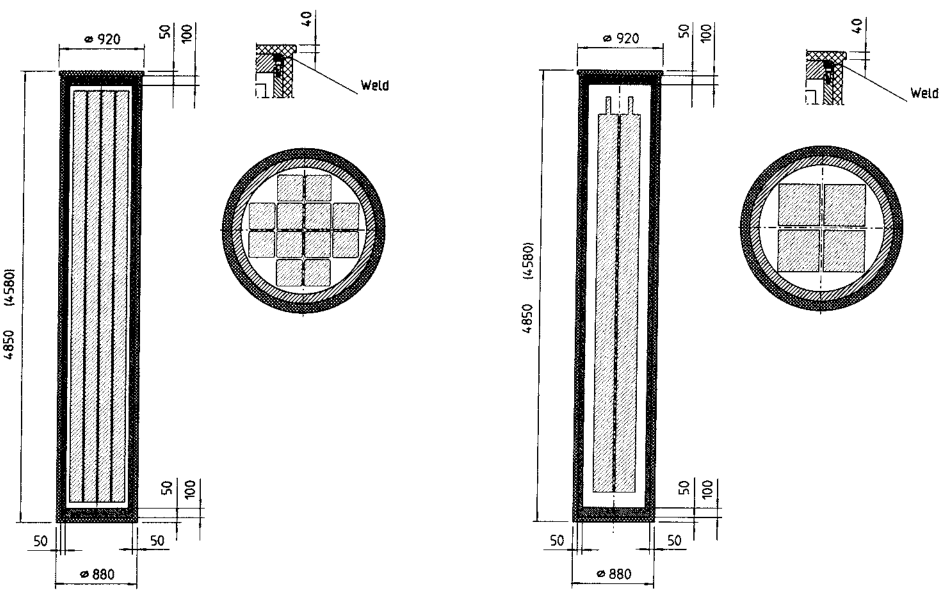

Figure 3-2. KBS-3 canister alternatives, ACP. The left canister is for BWR and the right canister is with PWR assemblies. The length within brackets refer to assemblies without boxes.

3.2.3 Barrier description

The canisters for spent fuel are assumed to be emplaced on a base pad of bentonite and surrounded by blocks of highly compacted water saturated bentonite in the deposition hole. The gap between the blocks and host rock is assumed to be filled with water, bentonite slurry or bentonite powder. Above the canister compacted bentonite blocks are positioned and finally the plugging zone in the deposition hole is filled with a sand/bentonite mixture compacted in several layers, see Figure 3–3.

The storage tunnel above the deposition holes will be filled with a sand/bentonite mixture and eventually the tunnel will be sealed with a plug consisting of concrete and/or highly compacted bentonite blocks.

The sealing of entrance tunnels and shafts are assumed to be performed mainly with a sand/bentonite mixture. The upper part of the shafts will be sealed with concrete and moraine to a depth of approximately 100 m below the surface.

Barrier material properties

The bentonite blocks surrounding the canisters are made of highly compacted sodium bentonite (MX-80) with an initial bulk density of 2.0 – 2.1 g/cm^3 with a high water content. The gap between blocks and the host rock has a width of approximately 1 cm and is assumed to be filled with water or a bentonite slurry.

The homogenized barrier surrounding the canister is assumed to have a bulk density of about 2 g/cm^3. The corresponding hydraulic conductivity is in the range of 10^{-14} to 10^{-13} m/s. The thermal conductivity of the homogenized barrier is assumed to be approximately 1.5 W/m,K.

The backfilling is performed with a 10 – 20 % bentonite sand mixture. The hydraulic conductivity is lower than 10^{-9} m/s.

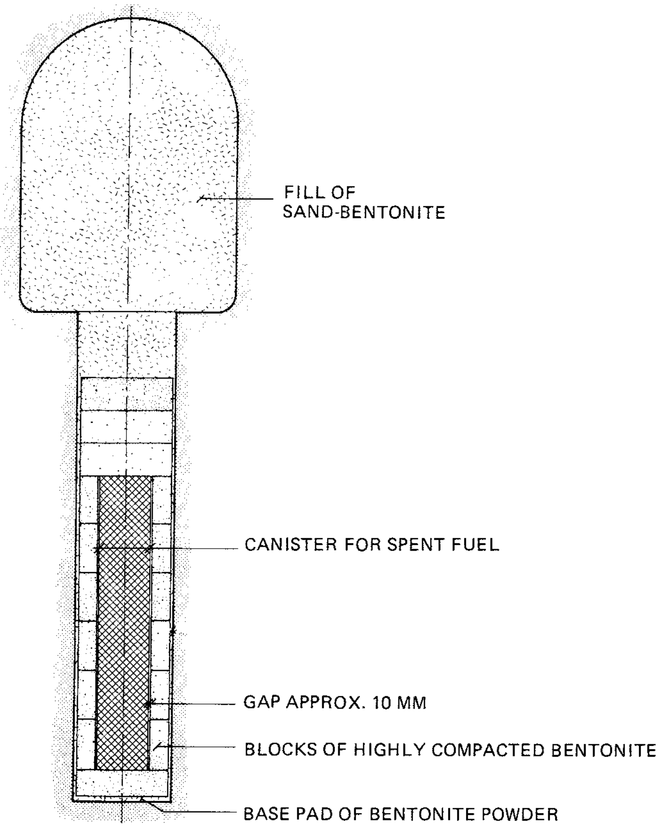

Figure 3-3. Deposition hole with canister and bentonite barriers.

3.2.4 Near-field rock description

The near-field of a repository is defined as the section around a canister which influences the release of the radionuclides once the canister is penetrated, i.e. the canister itself, the size and location of the penetration hole, the bentonite backfill and the rock closest to the deposition holes.

The rock properties in the near-field around the tunnels and the deposition holes.for the base case in SKB 91 has been defined by Pusch et al. [*1991*].

Near-field around tunnels

The near-field around the tunnels of a KBS-3 repository has in PASS been defined as:

- The repository will be located to avoid intersections by any 1st order fracture zones
- The tunnel orientation is assumed to be > 15° from the principle fracture orientation of the 4th order fractures
- The blast damaged zone is assumed to extend 1 m radially out from the tunnel and will have a hydraulic conductivity that is two orders of magnitude higher than the undisturbed rock. The stress-redistributed zone will have an extension of one tunnel diameter from the tunnel periphery and will outside of the blast damaged zone have an axial hydraulic conductivity that is increased one order of magnitude compared to the undisturbed rock.

- The cross section of the upper part of the tunnel will be designed to give effective arching and a minimum of radial displacement to minimise disturbances.

The definitions of the different orders of fracture zones and fractures are given in Appendix 6. Table 3-1 present the assumed hydraulic conductivities in the near-field around the tunnels.

In Figure 3–4 the conductivities and extension of the blast damaged zone and stress-redistributed zone are shown.

Table 3-1. Hydraulic conductivities in the near-field rock for the KBS-3 concept.

Location	Conductivity [m/s]
Undisturbed rock	10^{-10}
1 m out from drift	10^{-8}
1 drift diameter out	10^{-9}

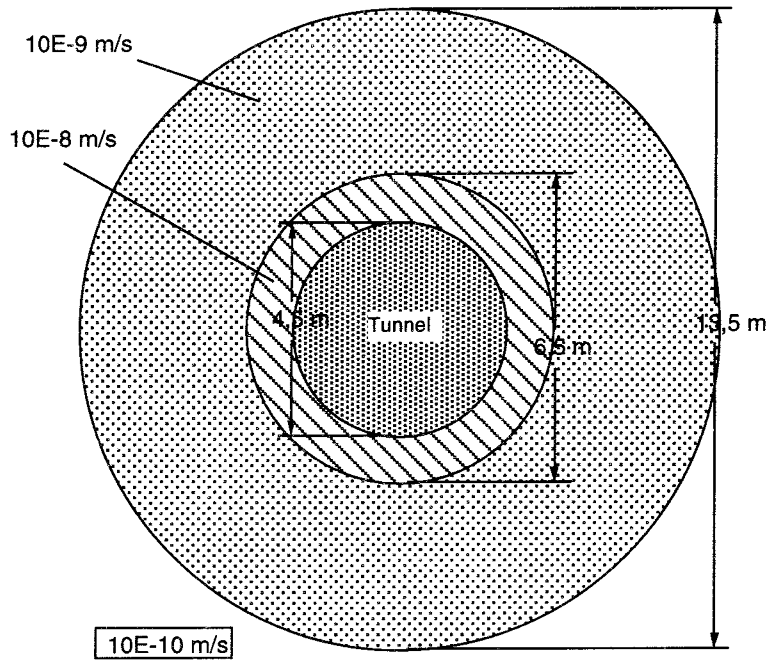

Figure 3-4. Schematic view of the different sections around the drift and their hydraulic conductivities.

Near-field around deposition holes

The near-field around the deposition holes will be defined by:

- All of the deposition holes will be intersected by at least 1 (in the range 1-3) 4th order natural fracture.

- A number of opened fractures will intersect all deposition holes.

- The deposition holes will be drilled, which will give a disturbed zone around the hole that stretch 3 cm into the rock resulting in a hydraulic conductivity one order of magnitude higher than in the undisturbed surrounding rock.

- In 20 % of the deposition holes, "wedges" are assumed to occur from stress relief. The opened fractures are assumed to have an aperture of 0.5 mm compared to 0.1 mm for the fractures not influenced by this phenomenon.

Figure 3–5 shows the conductivities around a deposition hole assumed in this study.

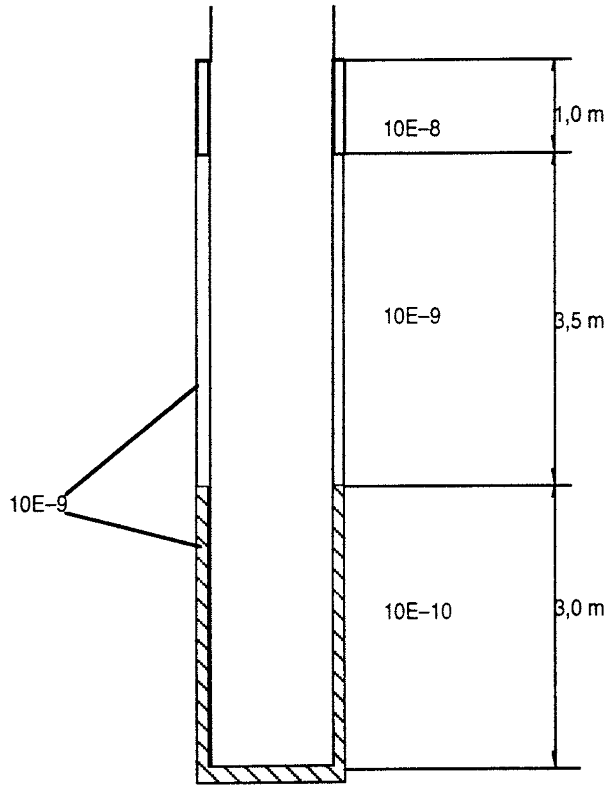

Figure 3-5. Schematic view of the different sections around a deposition hole and their hydraulic conductivities.

3.2.5 Far-field rock description

The repository layout in the KBS-3 concept is that the deposition tunnels and the canister holes are to be located in a 1*1 km plane. In this section the number of discontinuities of different orders that are expected to intersect a plane of this size is studied. In the future, when the actual repository is to be designed it is, however, possible to reduce the number of intersections with larger fracture zones. Information about the bedrock and existing fracture zones will continuously be obtained from investigation boreholes and from geophysical measurements. This information might lead to adjustments in the layout of the repository to avoid larger discontinuities. The compilation given in this section is, however, based on which discontinuities one would expect to find within a 1*1 km plane at the 500 m level. The hydraulic conductivities and spacings between the fracture zones are based on the discussion in Appendix 6.

Regional fracture zones (1st order), spacing 3200/6900 m, $K=10^{-7}$ m/s

Regional fracture zones have spacings of several kilometers. It should therefore not be a large problem to locate a KBS-3 type repository at least 1 km from any regional fracture zone. Regional fracture zones are therefore not considered to be of primary interest for the migration in the far-field.

Local fracture zones (2nd order), spacing 400/800 m, $K=10^{-8}$ m/s

Some 2nd order fracture zones will intersect the repository. The distance between these discontinuities is 400/800 m and a 1*1 km repository would typically be intersected by at least 2+1 (perpendicular respectively parallel to the dominating zone direction) 2nd order fracture zones. It might however be possible to avoid these zones if the repository is divided into, for example, three smaller areas. But even if the repository layout is adjusted to avoid these discontinuities it seems difficult to get larger respect distances than about 100 m. These 2nd order discontinuities are deemed to be important for the migration in the far-field.

Minor fracture zones (3rd order), spacing 50-100 m, $K=10^{-9}$ m/s

A large number of 3rd order fracture zones will intersect the repository. With a spacing varying between 50 and 100 m a 1*1 km repository would typically be intersected by 20-40 3rd order fracture zones. Due to the high frequency of these fracture zones it will be practically impossible to design the repository layout in a way that avoids these zones. The respect distance from these zones to the canisters will probably be a few, maybe up to ten meters. These zones are deemed to be of very large importance for the far-field migration.

Fractures (4th order), spacing 0.4/0.8 m, $K=10^{-11}$ m/s

The spacing between fractures is 0.4/0.8 m, but measurements indicate that the ratio between conductive and total number of fractures is about 1:10 giving a distance between water conductive fractures of about 4-8 m. Because of the high frequency it is unfeasible to even try to avoid these discontinuities. Fractures will intersect tunnels as well as deposition holes and the respect distance to the canisters will be negligible.

Subhorizontal fracture zones, spacing 700 m, $K=10^{-7}$ m/s

The spacing between these fracture zones and the quite limited extension of the repository, 1*1 km, indicates that the influence of these fracture zones could be small if the repository is properly located. The SKB 91 study indicates that a subhorizontal fracture zone located close and below the repository can be disadvantageous.

3.3 Very Long Holes - VLH

In the VLH concept the canisters are emplaced in horizontal tunnels, made by full face boring by Tunnel Boring Machines (TBM) at a depth of 500 m in the host rock. The artists view of the repository layout is presented in Figure 3–6.

3.3.1 Repository design

The repository area is in PASS assumed to be accessed by a steep ramp. The canisters will be deposited horizontally in three long parallel tunnels with a distance of 100 m between the tunnels. An investigation tunnel is situated 100 m below the deposition tunnels. Vertical shafts will also be included for supplies. The canisters with a diameter of 1.6 m will be surrounded by highly compacted bentonite blocks and deposited in the center of the tunnels that have a diameter of 2.4 m. To host the spent fuel (approximately 1 900 canisters) it has been assumed that three 4.5 km long tunnels are required [*Sandstedt et al., 1991*].

The canister presently foreseen within PASS (spherical ends) has a length of 5.7 m [*PASS, 1991*]. The total storage length has been assumed to be 13.5 km and the center distance between the canisters has been assumed to be about 6 m.

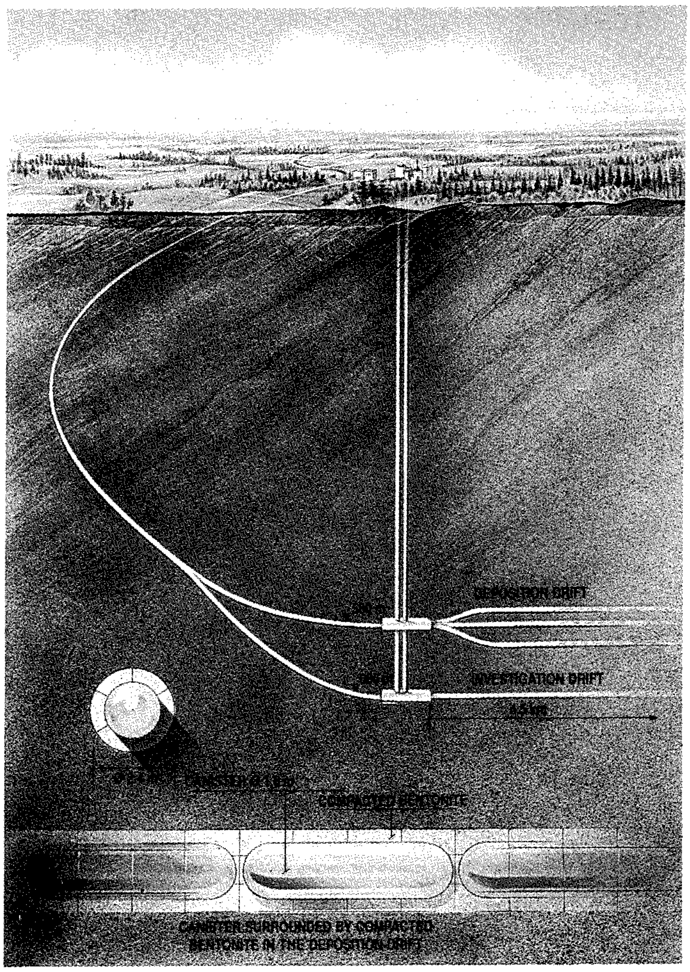

Figure 3-6. Artists view of the repository layout.

3.3.2 Canister alternative

In the VLH concept a copper-steel canister with an outer diameter of 1.6 m and hosting 24 fuel assemblies of the BWR-type is proposed, see Figure 3–7. This copper-steel canister consists of a 100 mm thick inner steel canister giving the support and an outer 60 mm thick layer of copper.

The canisters can have spherical ends to provide the most pressure retaining form or one could choose flat ends, see Figure 3–7. The lengths of a canister will be 5.7 and 5.0 m respectively with the same amounts of fuel assemblies. Both alternatives have voids of about 5 m^3 within the canisters.

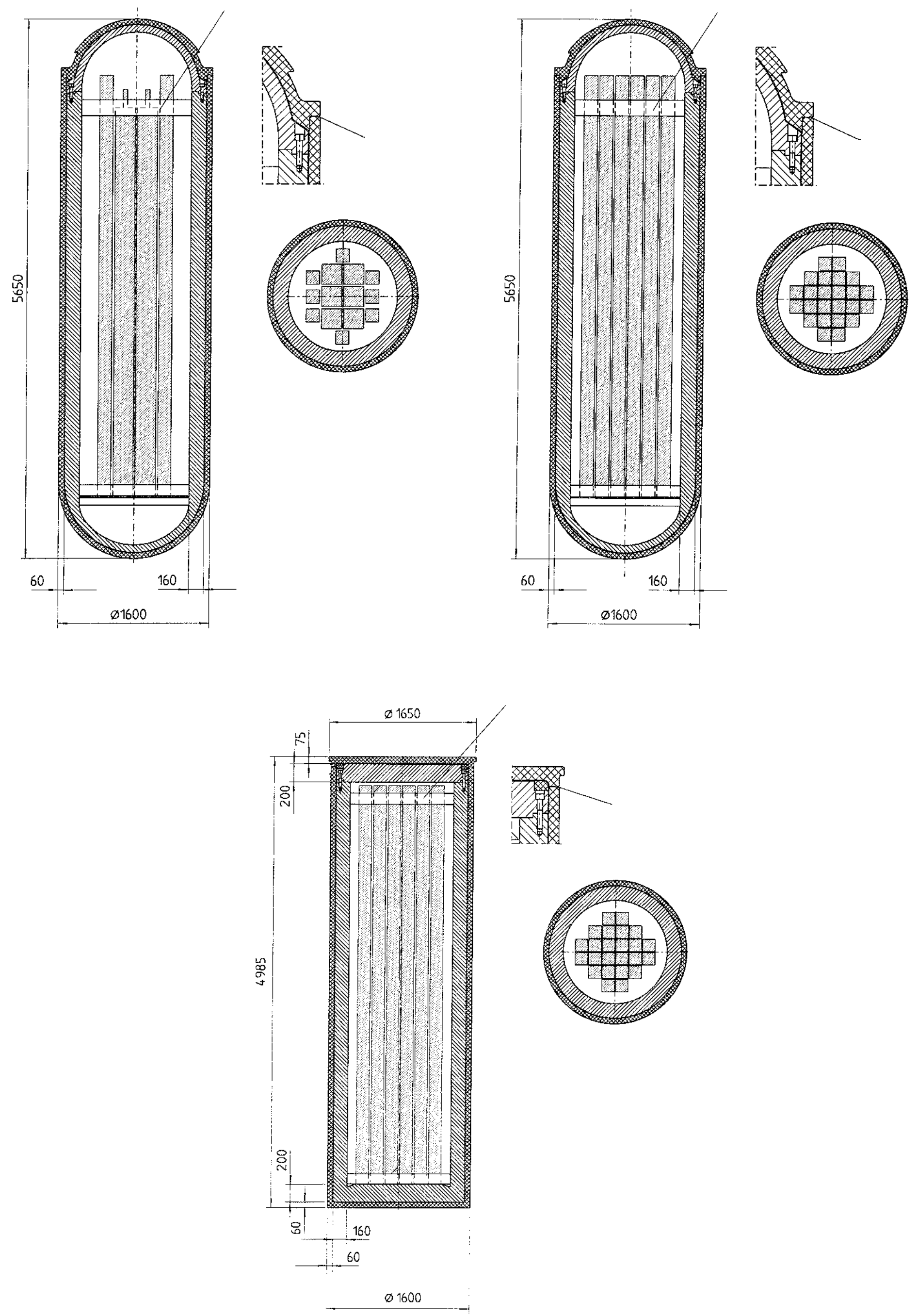

Figure 3-7. VLH canister alternatives. The upper right illustration is the design for both BWR and PWR assemblies.

3.3.3 Barrier description

In the deposition tunnel with a diameter of 2.4 m the canisters will be placed with a center distance of approximately 6 m and surrounded by 0.4 m thick bentonite blocks. In Figure 3–8 a schematic presentation of the canister and the barriers surrounding the canister in the deposition zone is given.

In the main concept the highly compacted bentonite blocks are assumed to be water saturated and the slots are assumed to be filled with bentonite slurry to ensure early saturation and a high heat conductivity. The thickness of the average slot between the bentonite blocks and the host rock is assumed to be 5 cm. After deployment the deposition tunnels will be totally filled with bentonite.

The access ramp and other tunnels and shafts will be sealed off by a mixture of sand and bentonite.

Barrier material properties

For a saturated bentonite buffer, the highly compacted sodium bentonite is assumed to have an initial bulk density of 2.08 g/cm^3 corresponding to a dry density of 1.76 g/cm^3.

The slot between the host rock and the bentonite block is assumed to be filled with a bentonite slurry with 400% water content and a density of 1.15 g/cm^3 equal to a dry density of 0.229 g/cm^3.

The homogenized barrier surrounding the canister will have a bulk density of 2.0 g/cm^3. The hydraulic conductivity is assumed to be about $2 \cdot 10^{-13}$ m/s. The thermal conductivity of the homogenized barrier is assumed to be 1.5 W/m,K.

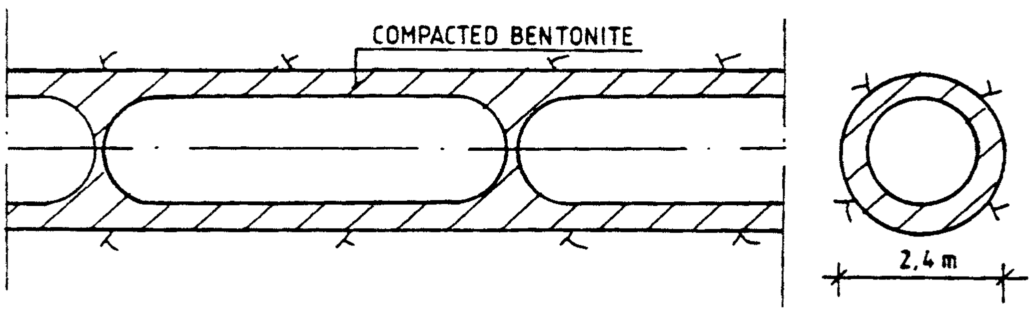

Figure 3-8. A schematic description of the deposition zone.

3.3.4 Near-field rock description

The drifts of the VLH-concept is proposed to be drilled by TBM-technique. This is considered to cause less disturbance to the rock surrounding the drift than blasting, even if smooth blasting is applied. A disturbed zone will be formed around the drifts caused by the stress release and other disturbances which will be obtained even when full face drilling is used. The types of disturbances around the VLH drift which are expected to be present directly after excavation are:

- thrust and fragmentation caused by the full face drilling
- stress release resulting from the excavation of the tunnels.

The first effect, thrust, is thought to extend for a few decimeters [*Pusch and Hökmark, 1991*] and fragmentation a few centimeters [*Pusch, 1989 and Pusch and Hökmark, 1991*] and give a hydraulic conductivity two orders of magnitude higher than the surrounding rock structure. The disturbance due to stress release will reach further out, in the order of the diameter of the drift [*Hökmark and Israelsson, 1991 and Pusch and Hökmark, 1991*] and will give an increase in conductivity of one order of magnitude compared to the undisturbed "averagely" fractured rock. In Table 3-2 a compilation of the estimated conductivities is made. In Figure 3–9 the conductivities and extension of the disturbances are shown.

Table 3-2. Hydraulic conductivities in the near-field rock assumed in PASS for the VLH-concept.

Location	Conductivity [m/s]
Undisturbed rock	10^{-10}
0.3 m out from drift	10^{-8}
1.8 m out from drift	10^{-9}

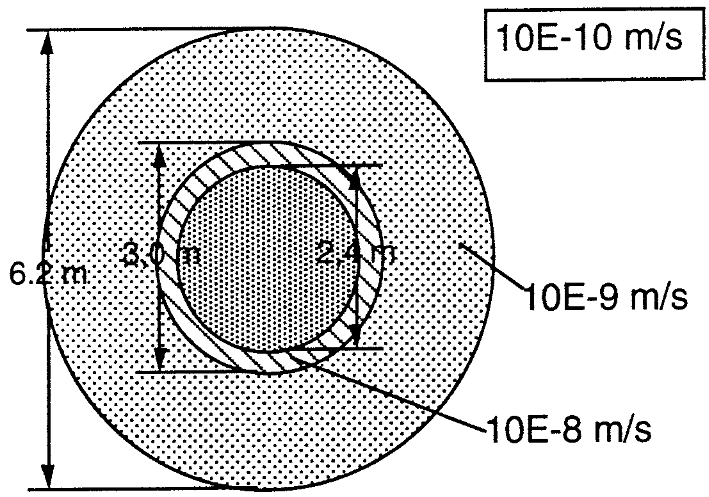

Figure 3-9. Schematic view of a VLH-drift and the hydraulic conductivities in its vicinity.

3.3.5 Far-field rock description

The canisters in the VLH concept will be located in three long parallel tunnels each extending for about 4.5 km. In this section the number of discontinuities of different orders that are expected to intersect a repository with this layout is studied. In the future, when the actual repository is to be designed it is, however, possible to reduce the number of intersections with larger fracture zones by just decreasing the length of the individual deposition tunnels or changing the orientation of them. The compilation in this section is based on which discontinuities one would expect to find within a 4.5 km long tunnel. The hydraulic conductivities and spacings between the fracture zones are based on the discussion in Appendix 6.

Regional fracture zones (1st order), spacing 3200/6900 m, $K=10^{-7}$ m/s

Regional fracture zones have spacings of several kilometers and it could be possible to locate a repository with a length of 4.5 km up to 1 km from any of those fracture zone. This is however based on that quite extensive geophysical measurements are performed prior to the excavation of the tunnels to ensure that all 1st order fracture zones are avoided since the extension of the repository tunnels are of the same size as the distance between the 1st order discontinuities. With a proper layout of the long holes, these fracture zones should not be of primary concern for the migration in the far-field.

Local fracture zones (2nd order), spacing 400/800 m, $K=10^{-8}$ m/s

Some 2nd order fracture zones will intersect the repository. The distance between these discontinuities are 400/800 m and a 4.5 km repository tunnel would typically be intersected by 5-10 2nd order fracture zones. It will not be possible to avoid these zones, and including an extra respect distance between the canister and the fracture zones will require extra tunnel length. A respect distance of 20-40 is assumed in this study. These 2nd order discontinuities are deemed to be important for the migration in the far-field.

Minor fracture zones (3rd order), spacing 50-100 m, $K=10^{-9}$ m/s

A large number of 3rd order fracture zones will intersect the repository. With a spacing between 50 and 100 m between these fracture zones a 4.5 km repository tunnel would typically be intersected by 50-100 3rd order fracture zones. It should therefore be difficult to obtain larger respect distances than a few meters to these fracture zones. These zones are deemed to be of very large importance for the far-field migration.

Fractures (4th order), spacing 0.4/0.8 m, $K=10^{-11}$ m/s

The spacing between water conductive fractures is about 4-8 m. With the proposed dimensions of the canisters, about one water conductive fracture will intersect the deposition tunnel at the location of each canister.

Subhorizontal fracture zones, spacing 700 m, $K=10^{-7}$ m/s

The spacing between these fracture zones is quite large. An extensive measuring program has to be performed to locate the repository in rock not influenced by these fracture zones because of the long extension of the tunnels in the VLH concept. The influence of these fracture zones should be small if the repository is properly located.

3.4 Medium Long Holes - MLH

In the MLH concept horizontal deposition of the canisters is made in a number of about 250 m long drilled tunnels with blasted access tunnels at both ends, see Figure 3-10. The repository is located at 500 m depth and the access to the repository is by ramp with shafts for auxiliary transports. The repository will probably, depending on the results of the site investigations, be designed with more than two parallel access tunnels with deposition tunnels between them.

The canisters are surrounded by compacted bentonite clay. In the MLH alternative a perforated metal casing is introduced between the canister and the bentonite to facilitate the installation of the canisters. This casing can be made of copper to avoid any effects of corroding steel in the vicinity of the canisters.

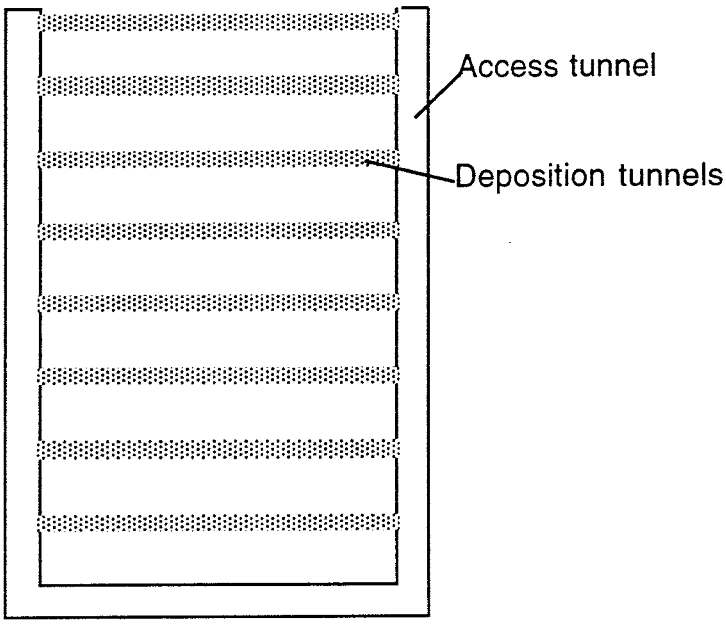

Figure 3-10. Layout of access tunnels and deposition tunnels for the MLH concept.

3.4.1 Canister alternative

The canisters are assumed to be identical in function with the ACP-canister described in Section 3.2.2 for vertical emplacement in the KBS-3 concept.

3.4.2 Near-field rock description

The access tunnels for the MLH concept will be excavated by drill and blast, and will have properties very similar to the tunnels above the deposition holes in the KBS-3 alternative. The deposition tunnels of the MLH concept are proposed to be drilled with raise-drilling technique. A disturbed zone will be formed around the drifts caused by the stress release and other disturbances that will be obtained. The raise-drilling technique is expected to cause disturbance to the rock surrounding the deposition tunnel similar to those caused by full face drilling with TBM-technique. The hydraulic conductivities around the deposition tunnels are therefore assumed to be the same as estimated by Pusch et al. [*1991*] for the VLH tunnels with a diameter of 2.4 m. In Table 3-3 the estimated hydraulic conductivities are presented and in Figure 3-11 the extension of the disturbances is shown.

Table 3-3. Hydraulic conductivities in the near field rock assumed for the MLH concept.

Location	Conductivity [m/s]
Undisturbed rock	10^{-10}
0.3 m out from drift	10^{-8}
1.8 m out from drift	10^{-9}

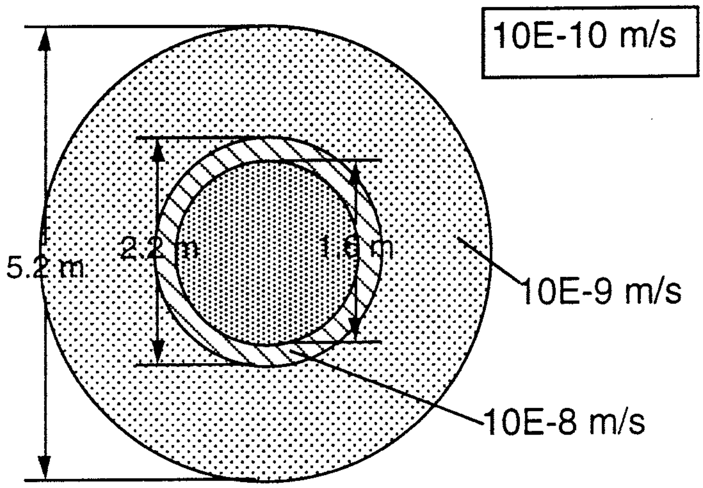

Figure 3-11. Schematic view of a MLH-drift and the hydraulic conductivities in its vicinity.

3.4.3 Far-field rock description

The far-field for the MLH concept is considered to be equivalent to the description given in Section 3.2.5 for the KBS-3 concept.

3.5 Very Deep Holes - VDH

In the VDH concept the canisters are deposited in very deep drilled holes at a depth of 2000 m to 4000 m in the host rock. In Figure 3–12 a schematic presentation of the repository layout is given .

3.5.1 Repository design

The repository design for the VDH concept is presented in [*Juhlin and Sandstedt, 1989*]. The drilling of the boreholes will be made by rotary drilling with a light bentonite mud. The respect distance between the boreholes is set to 500 m. The canister will be deposited in the deployment zone between 2000 m and 4000 m, where the borehole has a diameter of approximately 0.8 m and is equipped with an inner liner of non corrosive material with a diameter of 0.6 m. Above the deposition zone the borehole has a diameter of approximately 1.4 m and a casing of non corrosive material with a diameter of 1 m.

The available length for deposition per borehole is 2000 m. It has been assumed that 75 % of the deployment zone can be used for deposition of canisters. Approximately 300 canisters can be stored in each borehole. The reference amount of spent fuel 7 900 tonnes is in PASS assumed to require approximately 11 000 canisters.

In PASS, the canister is proposed to be of the same length as proposed in [*Juhlin and Sandstedt, 1989*] meaning a required storage length including a bentonite plug of 1 m of about 5.8 m.

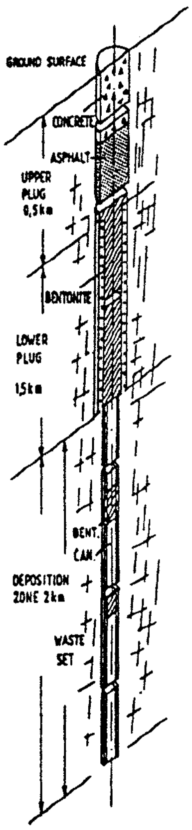

Figure 3-12. General view of the VDH concept.

3.5.2 Canister alternative

The general design of the VDH canister in PASS is a 6 mm thick titanium cylinder with a length of about 4.8 m and having an outer diameter of 0.5 m, see Figure 3–13. The canister will host 4 intact fuel assemblies of BWR-type. The void inside the cylinder will be filled with concrete.

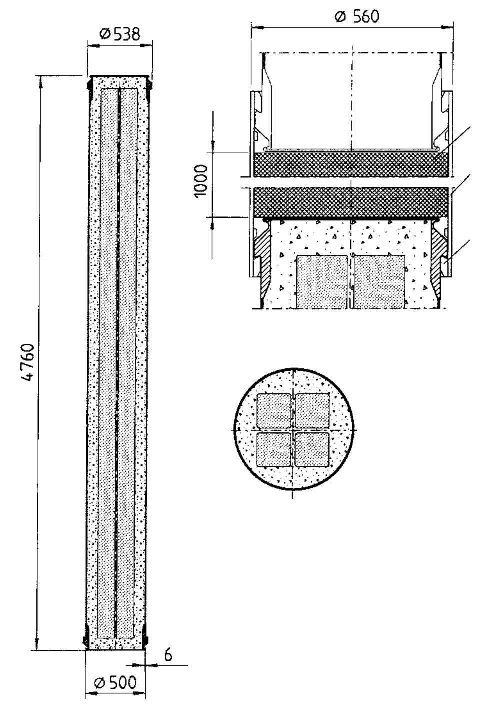

Figure 3-13. VDH canister.

3.5.3 Barrier description

The borehole can be divided in three parts, the deployment zone (2000 – 4000 m), the central part (2000 – 500 m) and the upper part (0 – 500 m).

In the canister deployment process the drilling mud will be replaced by a deployment mud with higher density. In the deployment zone the canisters with a diameter of 0.5 m will be surrounded by the deployment mud with a thickness of about 15 cm and separated by a cylinder of highly compacted sodium bentonite with a length of 1 m and diameter 0.5 m, see Figure 3–14. The casing, with a diameter of 0.6 m in the deployment zone, is proposed to be of titanium.

In the central part above the deployment zone the borehole will be sealed with highly compacted bentonite plugs. The drilling mud will be replaced by deployment mud during the sealing procedure.

The upper part will be sealed with a viscous material, asphalt, covered at the top by a concrete plug for protection against erosion and abrasion.

Barrier material properties

The initial dry density of the highly compacted sodium bentonite plugs is assumed to be 2.1 g/cm^3. The cylindrical blocks of sodium bentonite will be surrounded by deployment mud from which the blocks extract water and swell and at the same time the mud will be compressed. The hydraulic conductivity of the expanded bentonite plug is expected to be less than 10^{-12} m/s. After expansion the plugs will have a bulk density of about 1.9 g/cm^3.

The asphalt is expected to stay viscous for long-term periods and the hydraulic conductivity is near zero. The hydraulic conductivity of the concrete barrier at the top is expected to be approximately 10^{-11} to 10^{-10} m/s.

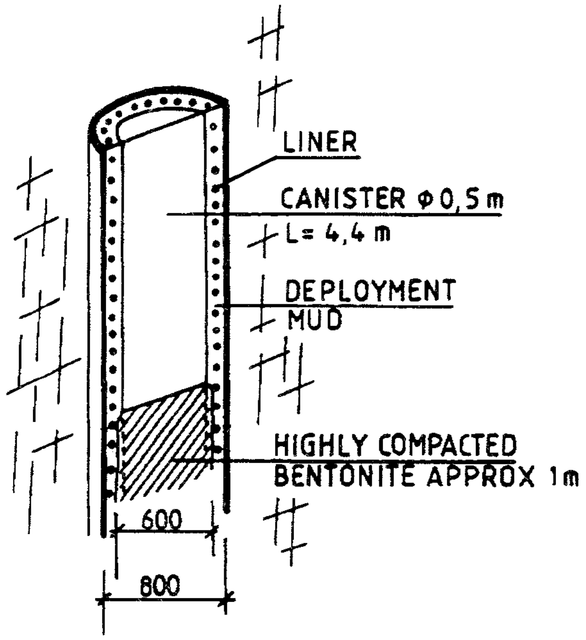

Figure 3-14. Deposition zone with emplaced canister .

3.5.4 Near-field rock description

The boreholes used for deposition in the VDH-concept are to be drilled to a depth of 4 km. The lower part of the holes, the deployment zone, is the part that is considered in this description of the near-field. A number of factors will cause disturbances in the rock close to the hole and thereby causing changes in the hydraulic conductivity in the near-field of a canister. These factors are:

- Load conditions during drilling and operational phase
- Penetration of mud into the rock
- Effects from pressure redistribution.

The first effects from the drilling are thought to extend in the range of a decimeter into the rock [*Pusch and Hökmark, 1991*] and result in a hydraulic conductivity three orders of magnitude higher than the surrounding rock structure. The disturbance due to stress release will reach further out, about 1 m [*Pusch and Hökmark, 1991*] and will give an increase in conductivity of two orders of magnitude compared to the undisturbed rock. Modeling of the effects of the mud indicate that significant penetration of the mud into fractures in the near-field is possible especially for the fractures with large aperture. Penetration depths of several meters is suggested. The mud that can penetrate into the fractures has a conductivity between 10^{-6} and 10^{-8} m/s and a density of 1300 g/cm^3. [*Pusch and Hökmark, 1991*]. In Table 3-4 a compilation of the estimated conductivities is made and in Figure 3–15 the conductivities and extension of the disturbances are presented. The hydraulic conductivity of the undisturbed rock is in this study assumed to be only one order of magnitude lower than the rock at the 500 m lever in order not to overestimate the barrier effect of the bedrock at depth.

To conclude, there will be a 0.1 meter section around the 0.8 meter diameter hole with an axial hydraulic conductivity of 10^{-8} m/s with the innermost 2 to 5 cm having a conductivity of 10^{-7} m/s. In a section up to 1 meter out from the hole perimeter the hydraulic conductivity will be raised two orders of magnitude compared to the rock further from the hole, i.e. 10^{-9} m/s compared to 10^{-11} m/s for the undisturbed rock [*Pusch and Hökmark, 1991 and Juhlin and Sandstedt, 1989*].

Table 3-4. Hydraulic conductivities in the near-field rock, for VDH-concept.

Location	Conductivity [m/s]
Undisturbed rock	10^{-11}
2 to 5 cm out from hole	10^{-7}
0.1 m out from hole	10^{-8}
1 m out from hole	10^{-9}

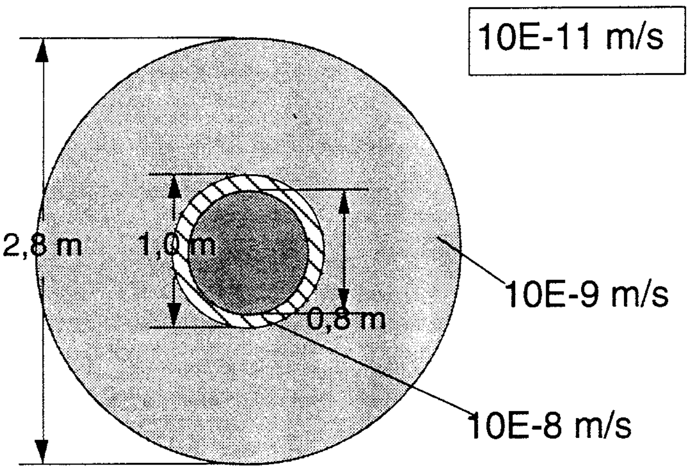

Figure 3-15. Schematic view of a VDH-concept and the hydraulic conductivities in the vicinity of the hole.

3.5.5 Far-field rock description

Rock at levels ranging from 2000 to 4000 m depth is significantly less described in the literature compared to rock at the 500 m level.

In Sweden the borehole, Gravberg-1, extends to such large depths. The Gravberg-1 borehole penetrated numerous fracture zones while being drilled. These fracture zones typically extend over 2-20 m and occur at a frequency of about every 200-300 m in the borehole, except in the upper 1200 m of the borehole, where they occur at a frequency of about every 50-100 m.

In the 12 km deep borehole at the Kola peninsula a fracture zone was found at about 4.5 km depth showing that it is possible to have permeable zones at large depths in crystalline rocks.

To sum up the observations from deep boreholes one can say that the frequency of fracture zones decreases with depth, the permeability decreases with depth, but measurements in the deep borehole at the Kola peninsula have shown that fracture zones with large permeability can be found at large depths. The available data are, however, not extensive enough for characterizing zones at great depths by orders and extensions.

3.6 Summary of basic assumptions

In this section the basic assumptions going into the comparison of the long-term performance of the alternative repository concepts are summarised.

In Table 3–5 a summary of the basic assumptions on canister and repository design is presented. In Table 3–6 the available essential properties of the different barrier materials are presented.

Table 3–5. Basic assumptions on canister and repository design.

	KBS-3	VLH	MLH	VDH
Canister type	Copper-steel	Copper-steel	Copper-steel	Titanium
diameter [m]	0.88	1.6	0.88	0.5
length [m]	4.9	5.0 or 5.7	4.9	4.8
center distance of canisters [m]	6	6	6	5.8
wall thickness [m]	0.05/0.05	0.06/0.16	0.05/0.05	0.006
number of canisters	3 745	1 873	3 745	11 235
BWR-elements	12	24	12	4
Repository				
level [m]	500	500	500	2000–4000
dimension	1 km^2	3 x 4.5 km	1 km^2	38 holes
access	ramp	ramp	ramp	–
Deposition zone	vertical	horizontal	horizontal	vertical
diameter [m]	1.6	2.4	1.6	0.8
barrier thickness [m]	0.36	0.4	0.4	0.15
length/ can. including barrier[m]	6.9	6	6	5.8
Plugging zone	1 per canister	1 per tunnel	2 per tunnel	1 500 lower plug
diameter [m]	1.6	2.4	1.6	1.4

Table 3–6. Basic assumptions on barrier properties.

	KBS-3	VLH	MLH	VDH
Bentonite in dep. zone				
bentonite quality	Na bentonite blocks	Na bentonite blocks	Na bentonite blocks	Bentonite mud and Na bent. blocks
density (initial) [g/cm^3]	2.0–2.1	2.08	2	1.6 + (2.2 and 1.6)
density (saturated) [g/cm^3]	2	2	2	1.9 (average)
hydraulic cond. [m/s]	2 10^{-13}	2 10^{-13}	2 10^{-13}	10^{-11} and 10^{-9}
thermal cond. [W/m,K]	1.5	1.5	1.5	1.0
Plugging zone				
backfill quality	sand/bentonite (80/20–90/10)	Na bentonite	Na bentonite	Na bentonite and bentonite mud
density (initial) [g/cm^3]				2.2 and 1.6
density (saturated) [g/cm^3]				1.9 (average)
hydraulic cond. [m/s]	10^{-9}			10^{-11} and 10^{-9}
Deposition tunnel		–		–
backfill quality	sand/bentonite (80/20–90/10)			
hydraulic cond. [m/s]	10^{-9}			
Shafts/ramp				–
	sand/bentonite	sand/bentonite	sand/bentonite	

4. REPOSITORY PERFORMANCE

4.1 General

In this chapter a general description is given of the expected repository performance after deposition of the waste packages. Phenomena that potentially will influence the properties of the barriers and thereby be of importance for the containment of radionuclides in the repositories are identified and described. To form a basis for the comparison of the four repository concepts, specific assumptions made regarding the short- and long-term performance are summarised in a reference scenario. Finally, potential effects of future events on the assumptions made regarding barrier performance in the reference scenario are identified and summarised in terms of a glaciation scenario and a human intrusion scenario.

4.2 Repository barrier performance

4.2.1 Introduction

In all four repository concepts both engineered barriers and natural barriers will limit the release and transport of radionuclides from the deposited waste to the biosphere. The engineered barriers are the canisters containing the waste and the clay material used as a buffer between the canisters and the rock in the deposition holes and the backfill in the access tunnels and shafts, as well as the top plug of asphalt and concrete in the deposition holes in the VDH-concept.

After the sealing of the deposition zones in the repository, the buffer material will take up water from the surrounding rock and gradually swell to form a barrier which mechanically protects the canisters and restricts groundwater flow. As long as the canisters are intact, no release of radionuclides from the repository will take place. Despite this, the time period prior to canister failure is important since phenomena occurring in and around the repository during this time may influence the life-time of the canisters as well as the properties of the other barriers at the time of canister failure. In the following sub-sections, processes and events which may influence the evolution of the barriers are identified and described.

4.2.2 Canister behaviour and potential failure modes

In this study the canister concept for KBS-3, VLH and MLH is a copper-steel composite canister and for VDH a titanium canister filled with concrete. After deposition, the canisters will be subjected to corrosion which may lead to canister failure. Phenomena resulting in mechanical impact on the canisters may also lead to canister failure. Finally, the possibility of initially defect canisters cannot, at present, be ruled out and is therefore addressed here.

Corrosion

Prior to saturation of the bentonite buffer surrounding the canister, gamma-radiation from the spent fuel penetrating the canister walls may lead to radiolysis of the moist air trapped in the pores in the bentonite buffer. As a consequence nitric acid may form and lead to some corrosion of copper. With an initially water-saturated buffer this process is negligible.

After homogenization of the bentonite buffer, corrosion of copper is caused by corrodants dissolved in the water. These are mainly oxygen and sulphide. Oxygen trapped in the buffer and backfill in the deposition holes/tunnels and transportation tunnels and shafts is dissolved in the groundwater and may during an initial time period lead to corrosion of the canisters.The amounts of oxygen from the atmosphere transported by the groundwater is in a longer time perspective expected to be small because of the negligible amount of dissolved oxygen in the groundwater at the repository depth. Oxygen is produced by radiolysis of water surrounding the canister because of penetration of gamma-radiation from the spent fuel in the canister. Sulphide is present in the groundwater and is continuously supplied to the canisters. In addition, the buffer materials in holes and tunnels act as a source since they contain sulphide. Potentially, sulphide may also be formed by microbial reduction of sulphate. Corrosion of copper by direct sulphate attack is kinetically hindered for temperatures below 100°C [*SKI, 1991*]. The effect of high salinity groundwater on copper corrosion is expected to be negligible [*Werme, 1990*].

In the copper-steel composite canister the internal steel walls will be subjected to corrosion when water penetrates the outer copper walls. Any oxygen present in the penetrating water is rapidly consumed and anaerobic corrosion of the steel material is initiated. Anaerobic corrosion of the steel canister proceeds under formation of hydrogen which to some extent can be dissolved in the water. Free hydrogen gas is formed if the corrosion rate reaches such values that more hydrogen is generated than can escape dissolved in the water.

Titanium is not thermodynamically stable in water. Under oxic conditions corrosion leads to the formation of titanium oxide. In the absence of dissolved oxygen corrosion proceeds under the formation of titanium oxide and hydrogen. Titanium oxide formed will passivate the surface, and as long as the passivating layer is intact, titanium will have a good corrosion resistance over a wide pH-range [*Mattsson, 1981*]. Studies in Canada suggests that with a high chloride concentration and high temperature the life-time of the titanium canister could be less than 10 000 years [*SKB, 1992*].

The corrosion rate of the canister materials is expected to be small if the surface is exposed to general corrosion, leading to a life-time of the order of 10^5 years for a titanium canister and millions of years for a copper-steel canister. Local attack on a small scale, pitting corrosion, may take place with significant higher corrosion rates. Crevice corrosion, for example in welds, and hydrogen embrittlement of titanium may also shorten the life-time of the canisters [*KBS, 1978*].

Internal corrosion of the steel vessel in the copper-steel composite canister is expected to be negligible as long as the copper canister walls are intact and no penetration of water has occurred [*Werme, 1990*]. However, in the case of a concrete filled titanium canister, the water in the concrete or oxidants produced by the radiolysis of the concrete water may initiate internal corrosion in an intact canister.

Mechanical failure

Mechanical failure of the canisters may be caused by internal pressure build-up or external mechanical stresses.

Helium gas, formed by α-decay in the fuel, will build up a gas pressure in the canisters. With an appropriate design of the canister what concerns initial void volume and design pressure it is not likely that the gas pressure alone will result in early canister failure.

When the bentonite buffer surrounding the canisters take up water and swell, the swelling pressure will increase until full saturation of the buffer is reached. As corrosion proceeds, the build-up of canister corrosion products, which are more voluminous than the canister material, will result in a compression of the bentonite buffer and an increase in swelling pressure. Also in this case, an appropriate design of the canister and the buffer will greatly reduce the risk of mechanical canister failure.

If rock movements occur in the close proximity of the canisters, this could potentially influence the canister integrity. However, the small rock movements that are expected are not likely to cause mechanical failure unless the canister is impaired by material defects.

Initially defect canisters

Despite an extensive quality control of the canisters before emplacement in the repository, manufacturing defects cannot, at present, completely be ruled out. Such defects are assessed to increase the potential for localised corrosion and also for mechanical failure of the canister if exposed to internal pressures or external loads and thereby significantly shorten the canister life-time.

Actions and unexpected events during transport and subsequent deposition of the canisters in the repository may cause damage to the canisters. In order to minimise the risk that this type of defect or damaged canisters are left in the repository, suspected canisters should be possible to control and, if necessary, possible to retrieve after deposition.

4.2.3 Short and long-term behaviour of the bentonite buffer and the backfill

In KBS-3, VLH and MLH, blocks of compacted bentonite will be positioned around the canisters in the deposition holes/tunnels. The storage tunnels in KBS-3 will be back-filled with a mixture of sand and bentonite. In VDH, the canisters will be surrounded by a dense bentonite fluid and separated by blocks of compacted bentonite. These buffer materials will take up water from the surrounding rock and expand. This water-saturation stage may to some extent influence the final properties of the water-saturated material. The long-term stability of the buffer and backfill depends on chemical alteration of the materials as well as on the behaviour of adjoining barriers.

Water-saturation

The bentonite in the deposition zone and the bentonite backfill in tunnels and shafts will take up water from the adjacent rock resulting in a swelling of the material. After water saturation and swelling, the bentonite material will have a low hydraulic conductivity, which restricts groundwater flow in the material, and a high swelling pressure, which leads to homogenisation and self-healing of the material. The initial density and composition of the bentonite material is of importance for the swelling pressure and hydraulic conductivity in the saturated bentonite material. Another factor that effects the hydraulic conductivity is the salinity of the groundwater.

The time to reach full saturation of the bentonite surrounding the canisters depends on the initial water content, the groundwater flow into the deposition zone from the adjacent rock, and also to some extent on the heat produced by the radioactive decay of the waste in the canister. This heat is transferred to the rock via conduction in the buffer material surrounding the canisters. The maximum temperature reached at the canister-buffer interface and the extension in time of the temperature pulse are dependent on design parameters (amount of spent fuel in each canister, canister dimensions, canister spacing, buffer dimensions) and also on the heat conductivity of the buffer and the surrounding rock.

During the saturation phase, the higher temperature in the buffer in the vicinity of the canister may result in evaporation of incoming groundwater with subsequent precipitation of elements in the groundwater. These precipitates may cause some cementation of the buffer material which may lead to a reduced swelling ability of the clay, but also to a decrease in hydraulic conductivity [*Pusch and Börgesson, 1992*]. These processes will not occur with initially water-saturated bentonite.

Chemical alteration

Interactions with components in the groundwater, reactions with canister corrosion products and the thermal load in the buffer may chemically alter the buffer material and thereby lead to changes in the physical and chemical properties. If the buffer material is a sodium-based bentonite, sodium will by ion-exchange be replaced by calcium from the groundwater. This will lead to a loss of some of the plasticity and swelling ability of the material.

Calcium in the groundwater may also chemically react with carbonate dissolved from the bentonite leading to a precipitation of calcite. This process is most likely during the high temperature period since the solubility of calcite decreases with increased temperature. Precipitation of calcite in the bentonite buffer (and backfill) may lead to a blocking of pores in the barriers and thereby to a reduced porosity. Another effect could be a loss of the initial elastic properties of the material with an increased risk of fracturing as a consequence.

Cementation of the bentonite buffer and backfill may also occur as a result of silica precipitation and transformation of smectite to hydrous mica [*Pusch and Karnland, 1990*]. Two different mechanisms have been suggested for this alteration process, and both mechanisms are controlled by the temperature and the access to potassium. At temperatures below 100–130°C a congruent dissolution of the smectite will occur at a rate determined by the temperature and the concentration of dissolved silica. On exceeding the solubility, silica will precipitate in the form of cristobalite or amorphous silica resulting in a cementation of the material and reduced swelling ability. If dissolved potassium is accessible, dissolved silica may instead react with potassium leading to formation of hydrous mica ("illite") [*Pusch and Börgesson, 1992*].

At temperatures above 100–130°C and with the presence of dissolved magnesium or iron in the pore water, a solid/solid transformation of montmorillonite to hydrous mica may take place in addition to neoformation of hydrous mica [*Pusch and Karnland, 1990 and Pusch and Börgesson, 1992*]. In this case lattice aluminum is replaced by magnesium or iron, and aluminum is through inter-lattice migration replacing silica which is dissolved from the laminar smectite layers. Silica is precipitated and the aluminum substituted smectite (beidellite) may transform to hydrous mica when sodium ions in the inter-laminar layers are replaced by potassium.

The consequences of both neoformation of hydrous mica and solid/solid transformation of smectite to hydrous mica are that the swelling ability of the clay is lost and that the hydraulic conductivity will increase. This change becomes specially severe in conjunction with rock displacements along fractures crossing a canister position.

Copper dissolved during the corrosion of the canisters may interact with the surrounding bentonite barrier by ion-exchange where sodium in the smectite is replaced by copper. This process occurs in competition with sodium-calcium exchange, and is also expected to have a similar effect on the physical properties of the clay as the sodium-calcium exchange [*Pusch and Börgesson, 1992*]. However, the solubility of copper in this environment is very low and consequently the effect of dissolved copper on the clay composition is expected to be minor.

Corrosion of the inner steel canister will result in the formation of solid iron oxide/ hydroxide and dissolved iron, and also in the generation of hydrogen gas. Dissolved iron in the pore water of the bentonite buffer may cause an ion-exchange between sodium and iron, with similar effects on the physical properties as expected for the sodium-copper exchange [*Pusch and Börgesson, 1992*]. If iron precipitates in the pores in the clay, the permeability of the clay will be reduced, but the precipitates will also have a cementing effect leading to reduced swelling ability.

The interior of the titanium canisters is proposed to be filled with concrete. After failure of the titanium canister, components dissolved from the concrete will migrate out through the ruptured canister and surrounding bentonite buffer. These components are primarily sodium, potassium, calcium and hydroxide ions. Sodium and calcium will interact with the bentonite material by an ion-exchange mechanism. Calcium dissolved from the concrete may also react with carbonate from the bentonite leading to a precipitation of calcite (see above). Potassium leached from the concrete may take part in the transformation of montmorillonite to illite.

Hydroxide ions dissolved from the concrete may interact with smectite in the bentonite buffer which may lead to the formation of zeolites and hydrosilicates. These minerals do not have the same elastic properties as smectite, and may therefore, if they are formed, increase the possibility of fracturing of the barrier. However, smectite has a high pH-buffering capacity [*Pusch, 1985*]. Another possible effect of the dissolution of concrete is the formation of brucite ($Mg(OH)_2$) in the pores in the bentonite material as a result of a chemical reaction between hydroxide ions from the concrete and magnesium ions in the groundwater. Precipitation of brucite will have similar consequences as precipitation of calcite, i.e. reduced porosity of the barrier but also a reduction in the elastic properties.

4.2.4 Short and long-term behaviour of the near-field rock

The integrity of the engineered barriers in the near-field are dependent of the conditions prevailing in the rock surrounding the backfill. A number of disturbances in the near-field rock have a potential to effect the release from the repository. These are:

- chemical effects
- thermochemical effects
- mechanical effects
- thermo-mechanical effects
- gas formation effects.

Chemical effects include the changes in redox conditions during the resaturation after closure of repository and the transport of components from alteration of the engineered barriers.

Thermochemical effects include the calcite precipitation due to the decreased solubility of calcium when the temperature is elevated and the dissolution of silica due to its increase in solubility with temperature. The precipitation of calcite may result in clogging of transport paths and reduce the water transport in the near-field, but this can be counteracted by the dissolution of silica. However, these two effects will not necessarily occur at the same locations, thus some transport paths can be widened and others may diminish.

Mechanical disturbances which may influence the hydraulic conductivity, other than those caused by the excavation of the tunnels and deposition holes and the stress redistribution, are caused by the swelling pressure of the bentonite around a canister. This swelling pressure may amount to 10 MPa and may therefore counteract the effect of the stress redistribution caused by the excavation. On the other hand the resulting radial stress close to the wall, which may amount to 15 MPa, may reduce the effective normal stress acting on fractures aligned with the axis of the deposition hole. Rutqvist et al. [*1991*] have shown that such a situation may cause a doubling of a pre-excavation aperture of 60 microns. The swelling bentonite will probably only penetrate a few millimeters, and thus the effect of the bentonite will probably not counteract the excavation effects to a significant amount. The swelling pressure in the storage tunnels filled with sand-bentonite mixture will only amount to approximately 1% of the swelling pressure in the deposition hole. Thus the counteracting effect of back-fill swelling in the storage tunnels may be neglected. Changes in rock stress, for example during glaciation, may potentially lead to rock movements and altered hydraulic conditions in the near-field rock.

Another process which has to be taken into account when discussing the long-term characteristics of the zone around a storage tunnel is the stability and longevity of the back-fill. If the backfill is deteriorated due to successive erosion, most possibly initiated in the not so well compacted crown of the storage tunnel, a high-conductive channel may develop in the upper part of the back-fill along the axis of the tunnel. In addition, the loss of support imposed by the eroded-away back-fill may result in caving in of the crown of the storage tunnel, thus enlarging the high-conductive channel.

Thermo-mechanical effects may occur by the opening and closure of fractures in the vicinity of the tunnels and deposition holes during a limited time period caused by the heat dissipation from the canisters. However, this effect is probably small compared to the permanently damaged zone created during the excavation.

Gas formation will occur inside the canister due to radiolysis and from the corrosion of the canister material, in case with an ACP-canister, after water has entered the canister. The pressure buildup inside the canister can cause piping of gas through the bentonite and cause gas to get in contact with the near-field rock. If the gas production exceeds the amount that can be dissolved in the available water a two-phase flow situation in the near-field rock is possible.

The long-term stability of the VDH boreholes is treated in [*Juhlin and Sandstedt, 1989*] where it is concluded that instabilities would most likely appear during the drilling. If stable borehole breakouts are formed, the stress can increase which in time may result in ruptures.

4.2.5 Short and long-term behaviour of the far-field rock

The hydraulic behavior of the far-field rock, which is of importance for radionuclide migration, might not be static but could change with time due to different effects. These are:

- chemical effects
- thermo-chemical effects
- mechanical effects
- thermo-mechanical effects.

Chemical effects include the changes in geochemistry, groundwater and mineral composition that might occur due to long-term changes in the far-field. These changes could for example be due to glaciations during which oxygen-rich surface water is forced to large depths.

Heat will be generated from a repository. This might cause thermo-chemical and thermo-mechanical changes even in the far-field. These effects should, however, be largest in the near-field where the temperature increase due to the heat generated by the fuel is more significant than in the far-field. The generated heat will also cause a thermal gradient that might affect the migration of the radionuclides. Mechanical effects as changes in rock stresses and major transport paths could for example be due to glaciations.

4.2.6 Short and long-term behaviour of the biosphere

The biosphere, usually regarded as the part of the Earth which contains living organisms, constitute the last barrier which will influence the exposure and dose to Man from radionuclides released from a repository. There are many potential pathways for the radionuclides in the biosphere including transfer between different physical compartments and transfer in food chains, and hence also a large number of processes which affect the radionuclide transport along these pathways. The main pathways of importance depends to a large extent on the nature of the radionuclide release from the geosphere and on the primary receptors in the biosphere. These primary receptors are usually considered to be a well/spring, a lake/river or its sediment, soil, and for a near-coastal or sub-seabed repository, the sea or its sediment. Because of the evolution in the biosphere as well as in the geosphere, the primary receptors and potential pathways and processes involved will vary with time.

The evolution in the biosphere can be expected to be much more rapid than in the geosphere. Geomorphological processes induced by wind, rain, ice, waves, river or soil water may lead to changes in the hydrological, physical and chemical characteristics of the primary radionuclide receptors in the biosphere [*Wiborgh et al., 1992*]. In addition, geomorphological processes may lead to changes in the vegetation which will affect the radionuclide transfer via crops and animals. Land uplift is another natural process which may alter the biosphere by changing the extension of the shore line.

Human activities may also induce some changes in the biosphere [*Wiborgh et al., 1992*]. Removal of sediments from lakes and rivers, changes of water courses (damming, regulation of flow), changes in land use, changes in agriculture practice, release of toxins to the environment, are examples of activities which may alter the biosphere receptors as well as the exposure pathways.

In a long-term perspective, effects of future changes in climatic conditions have to be considered. Over the next hundred thousand years it is expected that several periods of glacial advances and retreats will occur in Sweden [*SKI, 1991*]. Glaciation will drastically change the biosphere by, for example, removing soil and sediment covers, cause land uplift or land sinking as well as changes in sea level.

Climatic changes which may influence the evolution of the biosphere on a shorter time-scale cannot be ruled out. For example, the "greenhouse effect" may result in ice-cap melting and a subsequent rise in sea-level [*Wiborgh et al., 1992*].

4.3 Reference Scenario

4.3.1 Canister life-time

KBS-3

It is highly probable that the quality control after manufacturing will assure that no initially defect canisters are deposited in a KBS-3 repository. On the other hand, minor defects such as pores in the welds cannot be ruled out. Additional damage to the canisters during the transportation and deposition phase will not take place unnoticed, and the damaged canisters may be retrieved. Consequently it is judged plausible that all deposited canisters initially have a totally isolating copper shell, but pores or similar defects might provide weaknesses resulting in shorter integrity of the copper than otherwise could be expected. For the sake of comparison, however, one out of thousand canisters is assumed to have a defect already when it is deposited, a defect that penetrates the total thickness of the copper shell. This defect is assumed to be equal to the initial defect assumed in the SKB 91 calculations, a hole with a diameter of 2.5 mm After deposition of the canisters, groundwater can penetrate through the defect and reach the internal steel canister whereby local corrosion of the steel canister is initiated. This short circuit of the outer copper canister will reduce the canister life-time to the thousand of years scale from the potential million of years scale if the failure is caused by corrosion.

Failure of an initially intact canister because of helium generation inside the canister is not probable since the internal void in the composite canister should be large enough to prevent large pressure build-up. The mechanical resistance of the copper-steel composite canister is expected to be high at least as long as the inner steel canister is intact. This in combination with the protective properties of the surrounding bentonite buffer (see Section 4.3.2), makes it highly probable that the canisters will withstand external mechanical impact. The life-time of an initially intact canister should then be at least as long as the time for corrosion to penetrate the outer copper layer of the canister which has been estimated to be longer than 10 million years [*Werme, 1990*]. This estimate considers corrosion by oxygen trapped in the buffer and backfill, radiolysis products and sulphides, and localised corrosion is accounted for. Sulphide is assumed to be supplied from the bentonite in deposition holes and tunnels and by the groundwater.

VLH

In similarity to the KBS-3 canister, the copper-steel composite canister proposed for the VLH concept will be exposed to extensive quality control to avoid deposition of initially defect canisters, and damage of the canister during the deposition phase is not expected to occur unnoticed. To cover any deficiencies in the quality control the same assumption about small initial defects in the weld in some of the canisters is therefore motivated.

No significant pressure build-up of helium is expected which could result in canister failure. Likewise to the KBS-3 canister the life-time of an initially intact VLH canister exposed to corrosion is of the order of millions of years because of the expected slow corrosion of copper. The potential to withstand external mechanical impact during this time should be the same as in KBS-3. For calculation purposes one out of thousand canisters is assumed to have a defect already when it is deposited.

MLH

The MLH canister is the same type of canister as proposed for the KBS-3 concept. The assumptions about initial defect canisters and estimates about mechanical resistance and canister life-time must therefor be very similar.

VDH

Deposition and final positioning of the concrete filled titanium canister proposed for the VDH concept involves several operations which may result in damages of the canister [*Sandstedt, 1991*]. Furthermore, visual control of the canisters after deposition and retrieval of damaged canisters is not easily performed. Consequently, it cannot be ruled out that a large number of the canisters is damaged already after deposition.

Canisters which sustain the operations during the deposition phase will be subjected to both external and internal corrosion. Adsorption of hydrogen formed during the anaerobic external corrosion may result in hydrogen embrittlement of the titanium. Hydrogen is also formed inside the canister due to radiolytic decomposition of the water in the concrete increasing the risk of hydrogen embrittlement of the inner surfaces of the titanium canister. The combination of hydrogen embrittlement of titanium and potential external mechanical stresses and/or gas pressure build-up in the canister will increase the risk of canister failure.

Because of the large uncertainties associated with the canister integrity it is judged reasonable to assume that all canisters are initially damaged in comparison with the other concepts for which one out of a thousand canisters is assumed to have an initial defect.

4.3.2 Water penetration into canisters

KBS-3

An initial defect in the weld of the copper-steel composite canister can lead to water intrusion into the canister and will thereby result in hydrogen evolving corrosion of the inner steel vessel. The canister is assumed to be placed in the deposition hole so that the weld is at the top. Water will fill the slot between the steel and the copper. Water penetration will continue until hydrogen formed by corrosion has built up a pressure inside the canister which equals the hydrostatic pressure outside the canister. The amount of water inside the canister at this stage depends on the corrosion rate, the lower the corrosion rate the larger the amount of the interior void can be water-filled. Once the hydrogen pressure inside the canister exceeds the hydrostatic pressure outside the canister, additional hydrogen formation can reverse the water flow.

Anaerobic corrosion of the steel will continue until the water is consumed. A stoichiometric calculation shows that conversion of a water volume corresponding to the total void volume in the canister to hydrogen gas by anaerobic corrosion will consume approximately 50% of the initial amount of steel in the canister. Hence, the water is the limiting reactant. During this period the hydrogen pressure inside the canister will increase until it exceeds the sum of the hydrostatic pressure and the capillary pressure in the larger pores in the bentonite, and gas is released from the canister. The pressure for gas release through the bentonite is related to the swelling pressure of the bentonite [*Pusch, 1985*].

When all water inside the canister is consumed, corrosion is terminated and no more gas is produced. The canister is gas-filled, but the gas pressure inside will decrease because gas is escaping through gas channels in the bentonite and by diffusion. Gas will flow out through the bentonite until the pressure inside the canister has decreased below the capillary pressure of the largest pores in the bentonite. After that, the pressure will continue to decrease because hydrogen is dissolved in the porewater in the surrounding bentonite buffer and transported out through the buffer by diffusion. When the gas pressure has decreased below the hydrostatic pressure outside the canister, water may again enter the canister and corrosion is re-initiated. The hydrogen production will again increase the gas pressure and water intrusion is stopped when the gas pressure reaches the surrounding hydrostatic pressure. The gas pressure will continue to increase until no water is left inside the canister, and then again slowly decrease because of out transport of gas and out diffusion of dissolved hydrogen through the water-filled pores in the surrounding buffer. This type of cycling event will continue until all steel is consumed, and no more gas is formed by anaerobic corrosion. Taking into account the fact that dissolved hydrogen continuously may escape by diffusion through the water in the bentonite and water vapour may diffuse into the gas-filled canister it is possible that a steady-state situation is reached where the incoming water just balances the hydrogen formation.

When no more steel is left, the slow diffusion of gas out of the canister and subsequent decrease in gas pressure may with time allow transport of water into the canister which will fill the internal void. This void is smaller than the initial void in the canister because the corrosion products, due to their lower density, take up a larger volume than the steel metal and, due to their low solubility, to a large extent will remain at the location of corrosion.

The description above is focussing on anaerobic corrosion as the gas source. Radiolytic decomposition of water is another process which will result in the formation of hydrogen once the zircaloy rods are penetrated by corrosion or otherwise damaged, allowing water to come in contact with the fuel. This additional gas source is also dependent on the presence of water and is not expected to change the course of events other than possibly extend its duration if gas formation due to radiolysis still is significant when all the steel is consumed by anaerobic corrosion.

In summary it could be assumed that for a canister with an initial defect in the weld, this defect will shorten the life-time of the canister and determine the location of water penetration into the canister. The vertical placing of the canister in the deposition hole may result in accumulation of corrosion-generated hydrogen gas below the lid of the canister thereby reducing the risk of an early release from the canister of components dissolved in the water through the hole in the weld. The formation of hydrogen in gaseous form seems very probable since an extremely low corrosion rate, i.e. lower than $5 \cdot 10^{-10}$ m/year ($5 \cdot 10^{-4}$ µm/year) is required to maintain the generated hydrogen dissolved in the water (see Appendix 3).

With time, the presence of water and water vapour inside the canister may create a corrosion rupture in the bottom of the canister through which radionuclides may escape. However, as long as gas is formed inside the canister, water intrusion and thereby the amount of water in contact with the waste will be small. Furthermore, the formation of corrosion products will reduce the void inside the canister with times.

For a late failure of an initially intact canister, caused by corrosion alone or in combination with mechanical impact, the location of the failure is of importance. The consequence of a hole or crack in the top part of the canister is the same as described above for an initial defect in the weld. A failure at other places may lead to the displacement of water by gas. In case of a hole or crack in the bottom of the canister, gas may displace a contaminated water volume corresponding to the internal void of the canister through the damage in the canister bottom. The rate with which water is displaced depends on the gas formation rate and the resistance to flow in the canister break and surrounding bentonite buffer. Once the canister is emptied of water additional water intrusion is expected to be small and determined by the diffusion of dissolved gas out of the canister and water vapour diffusion into the canister as long as gas formation processes still are active.

VLH

The scenario for water penetration into a canister with an initial defect in the weld may be different in VLH compared to KBS–3. Because of the horizontal position of the canister in the deposition zone, the defect in the weld may face the bottom of the tunnel which means that hydrogen gas formed after water penetration may displace contaminated water through the hole in the weld. The maximum volume of water that may be displaced is also larger in a VLH canister by a factor of about 5.

For a late failure of a VLH canister, the scenario is similar to that for a KBS-3 canister except for the larger maximum volume of water that may be displaced from the canister interior by gas and that the potentially weakest point of the weld may face the bottom of the tunnel.

MLH

As for VLH, the scenario describing the penetration of water into a canister for MLH may be different compared to KBS-3. Because of the horizontal position of the canister in the deposition zone, the defect in the weld may be localised in the lowest part of the canister. This means that hydrogen gas formed after water penetration may displace water from the canister interior through the hole in the weld, and that gas inside the canister would not restrict nuclides to escape by diffusion. For late failure it is probable that the location of the penetration hole is at the weld so the same difference can occur as for initial damage.

VDH

Assuming that the titanium canister may be damaged initially after deposition, water will immediately have access to the canister interior with its concrete material and fuel rods. Radiolysis of the water close to the fuel (α) and of the water in the concrete (ß and γ) will result in the formation of hydrogen. As long as water is present in the concrete, hydrogen continues to form without reaching any equilibrium pressure [*Christensen, 1982*], but with a decrease in formation rate as the pressure increases [*Höglund and Bengtsson, 1991*]. Hydrogen may escape in dissolved form by diffusion in water-filled pores in the concrete and also in gaseous form through the largest pores or cracks in the concrete if the hydrogen pressure exceeds the sum of the hydrostatic pressure and the capillary pressure in these pores or cracks. Water may enter the concrete by capillary suction in smaller pores and by water vapour diffusion and capillary condensation.

For early times it could be assumed that the initially high dose rate and presence of water leads to the formation of gaseous hydrogen and a subsequent displacement of some of the contaminated water from the canister interior. As time proceeds, both the dose rate and the amount of water accessible to radiolytic decomposition decreases and a point is reached where the in-transport of water balances the out-transport of hydrogen. Because the dose rate and thereby the formation of hydrogen continues to decrease, the amount of hydrogen formed will be small enough to remain dissolved and escape by diffusion in the water-filled pores in the concrete and the surrounding buffer. Since no more gas is formed at this stage, the canister interior eventually becomes saturated with water.

4.3.3 Fuel dissolution and release from canisters

KBS-3

Once the canister is penetrated, water may enter and fill up the void inside the canister. With a water volume corresponding to the internal canister void and the amount of fuel stored in each canister the risk for criticality can at present not be disregarded [*Lönnerberg, 1992*]. This would result in a temperature increase which could damage the canister and the surrounding barriers and possibly have consequences for canisters in adjacent deposition holes. Since it is of primary concern to avoid criticality in the canisters it is in the following assumed that the canisters are filled with a material that eliminates the risk for criticality and is inert in all aspects except for potentially being a good sorbent for radionuclides.

When water has penetrated the canister and the zircaloy rod with the fuel, dissolution of the fuel is initiated. Some fission products, Cs, I, Tc and C, might be accumulated at the grain boundaries of the uranium fuel matrix. A fraction of these species also accumulate in the gap between the fuel and the zircaloy cladding and will be immediately dissolved as water enters the gap.

The rate of dissolution of the uranium matrix is dependent on the chemical conditions close to the fuel surface. Alpha-radiation from the fuel may decompose water in a thin layer in close proximity of the fuel resulting in the formation of hydrogen and oxidants such as oxygen and hydrogen peroxide. A recombination of the radiolysis products may occur. Alternatively, the formed oxidants may react with the uranium matrix oxidising uranium from the initial less soluble tetravalent oxidation stage to a more soluble hexavalent form. This oxidative conversion of the uranium matrix may also liberate other radionuclides incorporated in the matrix. Radionuclides which are solubility limited will re-precipitate and the concentration of these radionuclides in the water close to the fuel surface will be limited by their solubility in the type of chemical environment prevailing close to the fuel surface. The concentration of other radionuclides in the water in contact with the fuel is dependent on the rate of oxidative conversion of the uranium matrix.

If the water that comes in contact with the uranium matrix contains Fe(II)-ions from, for example corrosion of steel, oxidants from radiolysis of water may oxidise Fe(II) to Fe(III). The amount of oxidants available for oxidation of the uranium matrix will thereby be limited and hence, the rate of oxidation of the uranium matrix. Uranium and other redox sensitive radionuclides that are oxidised inside the zircaloy rod close to the fuel surface may during their transport in the canister be exposed to Fe(II) and once again be converted to a lower oxidation state. Since the solubility of Fe(III) is lower than the solubility of Fe(II) the oxidation of iron may also result in precipitation of Fe(III)oxides/hydroxides which have a strong ability to sorb radionuclides [*Koppi and Klessa, 1992*].

For the case with an early failure of a copper-steel composite canister caused by an initial defect in the weld it can be assumed that the fraction of fission products contained in the gap between fuel and cladding is immediately dissolved in the water intruding the canister and zircaloy rods. Radiolysis of a thin water film on the fuel surface initiates oxidation of the uranium matrix and dissolution of uranium and other radionuclides incorporated in the uranium matrix. Dissolved radionuclides are transported by diffusion, and possibly also by thermal convection because of the heat generated by the fuel, to other parts of the canister interior. The presence of Fe(II)-ions in the water from corrosion of steel will result in re-precipitation of uranium and other redox sensitive radionuclides with lower solubility at the lower oxidation state. Simultaneously, solid Fe(III)oxides/hydroxides may form onto which radionuclides can sorb. Gas, generated by corrosion of steel, accumulated in the top of the canister interior restricts the escape of dissolved radionuclides through the hole in the weld. As time and corrosion proceeds, water is consumed and precipitates are formed which will limit further radiolysis and dissolution as well as transport of radionuclides in the canister. Eventually, additional breaks in the canister may be created and dissolved radionuclides may escape through these breaks with a release rate dependent on the dominating transport mechanism and the size of the break.

For a late failure and subsequent water intrusion into a copper-steel composite canister hydrogen gas formed by corrosion of the steel interior may, depending on the location of the failure, displace water containing the gap-fraction of the readily dissolvable fission products. The restricted contact between fuel and water because of the accumulation of gas as well as the low dose rate expected after long times will limit the radiolytic oxidation of the uranium matrix and thereby also the concentration of radionuclides in the expelled water. In addition, the presence of Fe(II)-ions in the water may further reduce the concentration of redox sensitive radionuclides which have a lower solubility in the lower oxidation state. After the initial displacement of water radionuclides may continue to escape from the canister by diffusion. The continuous decrease in dose rate and the formation of gas and steel corrosion products will restrict the dissolution and escape of radionuclides from the canister interior.

VLH

In similarity to the KBS-3 canister, there is some risk for criticality in an unfilled canister [*Lönnerberg, 1992*]. It is therefore also here assumed that, if future studies conclude that it is necessary, the canister is filled with an inert material with such properties that criticality after water penetration can be excluded.

As mentioned earlier, the horizontal position of a canister in the VLH concept may lead to an early displacement of water by gas if the canister has an initial defect in the weld. The expelled water will contain the fraction of fission products that are easily accessible for intruding water, but will also contain uranium and other radionuclides incorporated in the uranium matrix. The concentration of uranium and incorporated radionuclides in the displaced water is determined by their solubility or by the radiolytic oxidation rate of the uranium matrix. The enhanced temperature inside the canister at early times compared to longer times may mean an increased solubility of radionuclides and thereby a higher concentration in the displaced water compared to a late canister failure.

The scenario for fuel dissolution and escape of radionuclides in case of a late canister failure is expected to be similar to the scenario for a late failure of a copper-steel canister in KBS-3. One difference is the relation between the amount of fuel and internal void in the canisters which is of importance for the concentration of non-solubility limited radionuclides in the water in the canister and thereby also for the rate with which radionuclides escape from the canister. A VLH canister contains twice as much fuel as a KBS-3 canister, but the initial internal void is approximately 5 times larger provided that the canisters are filled with materials giving the same porosity. The concentration of non-solubility limited radionuclides inside a VLH canister will thus be lower than in a KBS-3 canister. On the other hand, the larger amount of fuel in each canister means that more radionuclides may escape per failured canister.

MLH

In both the KBS-3 and MLH alternatives, the disturbed zone around the access tunnels and drifts, especially in the roof, may attract a large portion of the water flow through the repository. A difference between the KBS-3 and MLH concepts is that in the horizontal case the disturbed zones around the deposition tunnels may act as hydraulic conductors between the access tunnels, while the deposition holes in the vertical alternative are "dead-end" constructions. Thus, there may be a larger groundwater flow in the disturbed zone around the deposition tunnels in MLH than around the deposition holes in KBS-3. The flow in the disturbed zone around the deposition tunnels will depend on the pressure distribution in the near-field and the magnitude of the flow may be estimated by model calculations. A "dead-end" construction is also possible for the MLH concept by "stopping" the boring some distance from the machine side and thus leaving a rock plug between the access tunnel and the disposal tunnel.

Another difference is that the average distance from a canister to the larger access/storage tunnel will be longer in the MLH alternative than in the KBS-3 alternative. Thus, the disturbed zone around the deposition tunnels may constitute an additional barrier. Furthermore, if the disturbed zone around the deposition tunnels in MLH is the preferred pathway for radionuclides released from the bentonite, it may prevent direct nuclide transport to subhorizontal fracture zones in the neighborhood of the deposition area, c.f. hydraulic cage in the comparison between KBS-3 and VLH above.

The combination of disturbances from the tunnel blasting and the drilled, vertical deposition holes in KBS-3 may give rise to rock movements creating additional pathways in the rock around the upper part of the deposition holes. In MLH, this type of disturbances may also occur at the exits of the deposition tunnels. However, this will mainly affect the canisters adjacent to the access tunnels. Furthermore, the impact of such disturbances may be reduced by increasing the distance between the access tunnel and the first canister in the deposition tunnel.

VDH

With the proposed design of a VDH canister what regards the amount of fuel and internal void accessible to water, there should be no risk for criticality inside the canister [*Lönnerberg, 1992*].The initial water content in the concrete inside a VDH canister and the fact that the integrity of the titanium canister cannot be guaranteed after the deposition operations means that the chemical environment inside the canister already initially after deposition may be such that leaching of radionuclides from the fuel may take place. Temperatures above 100°C may initially prevail inside the canisters because of the elevated natural temperature at depths corresponding to the deployment zone in the holes (36–68°C at 2–4 km depth [*Pusch and Börgesson, 1992*]) and the additional temperature increase caused by the heat from the decaying fuel. These high temperatures introduces uncertainties what concerns the chemical processes occurring inside the canister.

Calculations performed by Christensen and Bjergbakke [*1987*] have shown that the yield of hydrogen and oxidants from α-radiolysis of water is independent of the temperature in the range 20 to 180°C. Furthermore, a somewhat lower yield was obtained assuming a pH of 12.5 compared to a pH of 8.5. These results indicate that the radiolytic oxidation of the fuel is restricted by the elevated pH in the water due to the presence of concrete. If more hydrogen is formed by radiolysis of the water than can escape from the canister interior, gas will be formed which may limit the contact area between water and fuel. This could further restrict the radiolytic oxidation of the fuel.

With the uncertainties in mind regarding the processes of importance for radionuclide dissolution and escape from the canister it is assumed that the easily dissolvable fraction of the fission products contained in the gap between fuel and cladding is immediately dissolved in the water close to the fuel. Radiolytic oxidation of the uranium matrix results in dissolution of uranium and liberation of radionuclides incorporated in the uranium matrix. This oxidative conversion of the uranium matrix or the solubility limits will determine the concentration of radionuclides in the water inside the canister. The high pH buffered by the concrete and the elevated temperature as well as the redox conditions inside the canister are important for the concentration of solubility limited radionuclides. Initially reducing conditions will prevail inside the canister except close to the fuel surface.

The dissolved gap-fraction of fission products and radionuclides leached from the uranium matrix may escape by diffusion through the water-filled pores and cracks in the concrete. Potentially, hydrogen in gaseous form from radiolysis of water can influence the escape of radionuclides by displacing water containing radionuclides through larger pores or cracks in the concrete. During the transport through the concrete radionuclides will sorb on the concrete surfaces thereby lowering the nuclide concentration in the water.

With time, the radiolytic oxidation rate of the fuel will decrease as a result of the decrease in fuel dose rate and possibly also because the presence of gas may restrict the contact between fuel and water. When the dose rate has decreased to a level where formed hydrogen may escape by diffusion, gas will no longer be present inside the canister. Continuous leaching of sodium, potassium and calcium from the concrete and diffusive out-transport of these components will increase the porosity of the concrete and decrease its mechanical stability as well as decrease its hydraulic resistance. Leaching of the concrete will also result in a decrease in pH from an initial value larger than 12.5 to a value of about 10.4 [*Höglund and Bengtsson, 1991*]. Although the hydraulic resistance and mechanical stability of the concrete eventually is lost, the concrete will still act as a barrier to many radionuclides because of its remaining high sorption capacity [*Allard et al., 1991*]. An additional process that may influence the dissolution and escape of radionuclides is the potential precipitation of redox sensitive radionuclides in the pores in the concrete and movement of the redox front.

4.3.4 Radionuclide transport in the near-field barriers

The transport in the near-field barriers includes the transport through the bentonite barrier, and in the disturbed zone surrounding deposition holes and tunnels. The subsequent transport in the far-field is discussed in Section 4.3.5.

KBS-3

The extent to which the bentonite will act as a barrier for escaping radionuclides depends on the degree of alteration prior to and after canister failure. If unsaturated bentonite blocks are used precipitation of elements present in the groundwater during the water-saturation phase because of unsaturated conditions and high temperatures could lead to cementation of the barrier with a reduced swelling ability and brittleness as a consequence. However, considering that the time needed for full saturation of the bentonite will be on the order of tens of years [*Pusch and Börgesson, 1992*], this process is not considered to be of major importance for the long-term properties of the bentonite. Furthermore, this type of cementation will be avoided by using a bentonite with a high initial water content.

After water-saturation, the low hydraulic conductivity in the bentonite ($K=10^{-14}$ - 10^{-13} m/s) will restrict the groundwater flow, and diffusion will be the dominating transport mechanism. Chemical alteration due to ion-exchange with calcium in the groundwater may with time increase the hydraulic conductivity by approximately one order of magnitude. Another process that may increase the hydraulic conductivity is the transformation of montmorillonite to hydrous mica (illite), see Section 4.2.3. According to Pusch and Börgesson [*1992*] all montmorillonite is transformed to hydrous mica when an uptake of potassium corresponding to roughly 10% of the solid mass of montmorillonite has taken place. Based on a potassium concentration in saline groundwater of 13 mg/l (see Appendix 6) in the groundwater at 500 m depth an estimate is given in Appendix 2 of the time needed for the alteration front to move through the bentonite surrounding the canister. Potassium is assumed to be transported by diffusion through the altered bentonite from the groundwater passing along the outer surface of the bentonite. The time needed for conversion of the bentonite surrounding a deposition hole into illite was found to be on the order of 300 000 years neglecting any kinetics involved in the transformation reactions. However, this requires that the groundwater flow is large enough in the vicinity of the deposition hole to allow for a continuous supply of potassium, or that the kinetics of the dissolution of the potassium bearing minerals in the near-field rock and the transport of this potassium to the surface of the bentonite is fast enough to balance the diffusion of potassium into the bentonite. This does not seem to be very likely. If the conversion of bentonite into illite is limited by the groundwater flow in the disturbed zone, see Appendix 2, conversion is estimated to take million(s) of years with a potassium concentration of 13 mg/l. The backfill in the tunnels will consist of a sand/bentonite mixture, but the amount of bentonite will likely be large enough to assure that only a minor part of the bentonite will be converted into illite within a time period of million(s) of years. The conclusion from the above discussion is that the bentonite buffer is likely to be chemically/mineralogically intact for time periods relevant for the radioactive waste. The transport of escaping radionuclides in the bentonite buffer will therefore be controlled by diffusion except for short periods when water can be displaced through the buffer because of the high gas pressure induced by corrosion within the canister, see Appendix 4.

Radionuclides escaping a canister will be diluted in the pore water and be delayed because of sorption on the bentonite surfaces. This delay will significantly reduce the amount of released short-lived radionuclides.

The flowpaths of main interest in the near-field for escaping radionuclides are the disturbed zone that will surround all drifts and, if close to the deposition hole, subhorizontal fracture zones. Radionuclides escaping from a penetrated canister must , however, be transported from the canister to one of the larger flowpaths, see Figure 4–1.

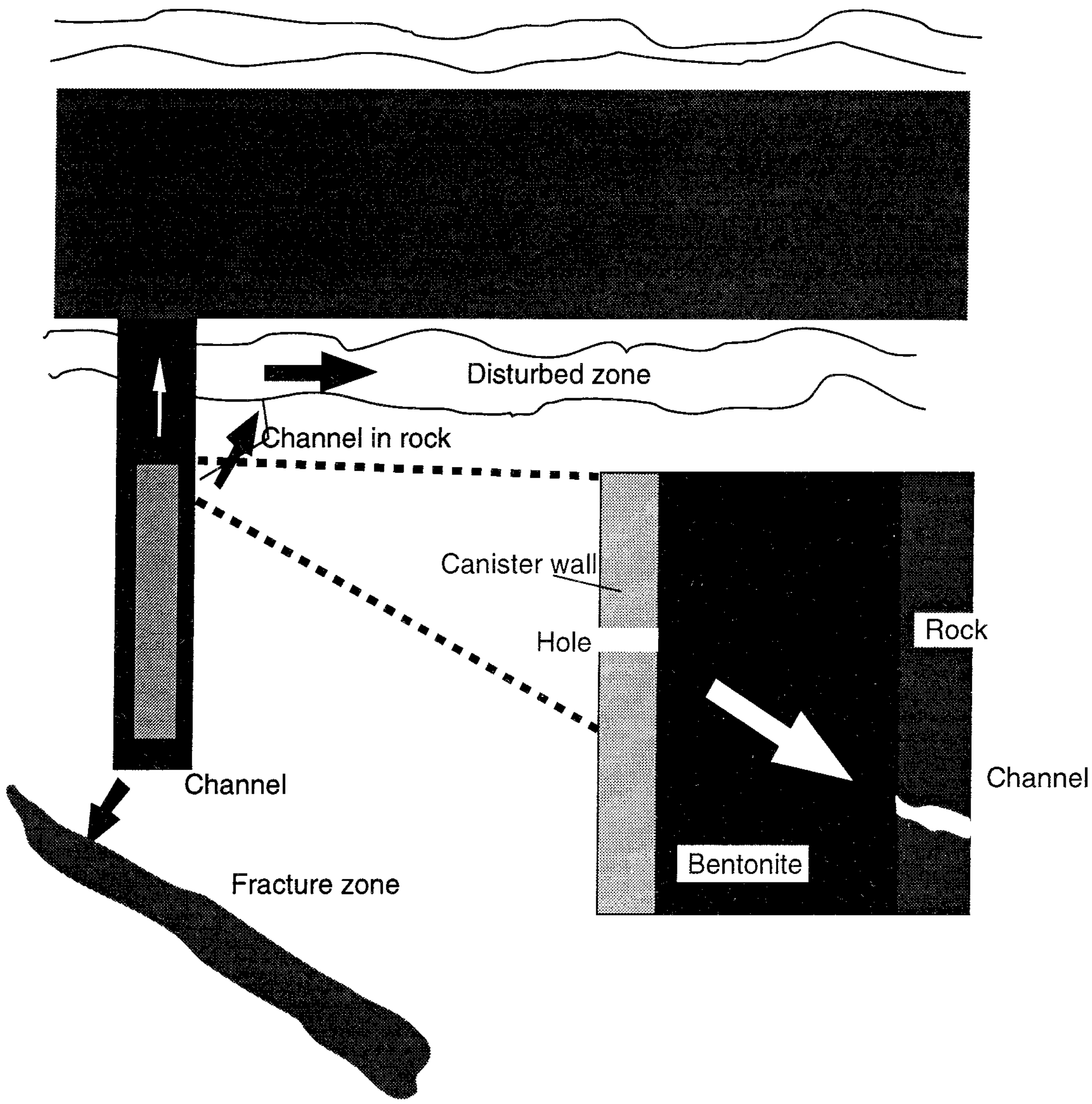

Figure 4-1. KBS-3. Transport pathways for radionuclides in the near-field.

The identified migration paths for the radionuclides are:

1: Diffusion through the bentonite to the disturbed zone surrounding the deposition hole and subsequent transport in the disturbed zone surrounding the deposition hole, or through a fracture intersecting the deposition hole, to the disturbed zone around the drift.

2: Diffusion upwards in the bentonite in the deposition hole to the disturbed zone around the drift.

3: Diffusion upwards in the bentonite in the deposition hole to the backfill in the drift, and subsequent transport into the disturbed zone around the drift or directly into fractures/ fracture zones intersecting the drift.

4: Diffusion through the bentonite and transport through the rock to a fracture zone located close to a deposition hole.

The escaping radionuclides must in all cases migrate a distance through the bentonite barrier in order to emerge in the disturbed zone or a fracture zone in the vicinity of the deposition hole.

In all cases the diffusional transfer of nuclides from the buffer to the groundwater flowing in fractures outside the buffer constitute an extra transport resistance. The magnitude of this resistance is dependent on the water velocity, geometry, contact time, contact surface and the diffusivity of the nuclide. Most of these parameters will be dependent on where the nuclide will pass from the bentonite/backfill into the disturbed zone surrounding the deposition hole/tunnel.

In case 1, the radionuclides have to migrate at least about 0.4 m in the bentonite surrounding the canister before entering the disturbed zone around the deposition hole. The radionuclides can then migrate either in the disturbed zone around the deposition hole or within a fracture intersecting the deposition hole and connected to the disturbed zone around the tunnel. The distance between the bentonite/deposition hole interface and the disturbed zone around the tunnel will be in the order of meter/meters dependent on the location of the canister failure. The fracture intersecting the deposition hole and the disturbed zone around the drift, see Figure 4–1, will probably be a 4th order fracture since these are order(s) of magnitude more common than larger discontinuities, see Appendix 6. 4th order fractures are assumed to be found with a spacing of 0.4-0.8 m in crystalline rocks at 500 m depth, but only 10 % of these fractures are water conductive giving an average distance between water conductive fractures of 4-8 m. 4th order fractures located in rock at the 500 m level has an assumed hydraulic conductivity of about 10^{-11} m/s. A fracture located in rock where stresses are altered due to the presence of the deposition hole as well as the drift might, however, have a significantly increased hydraulic conductivity. The hydraulic conductivity in the disturbed zone around the deposition hole is estimated to be about 10^{-9} m/s.

In case 2, the transport distance for the radionuclides in the bentonite will be dependent on the location of the hole in the canister, but will be considerably longer than the 0.4 m mentioned for case 1. A probable location for a failure in the canister is in the weld which if the weld is located at the top will give a diffusion distance of more than one meter.

The transport distance for the radionuclides in the bentonite will be longer in case 3 compared to case 2. However, the resistance which is connected to the diffusional transfer of nuclides from the backfill to the groundwater may be low if the nuclides are released directly into high conductive fracture(s) intersecting the backfill.

Subhorizontal fracture zones may have high hydraulic conductivities, on the order of $K=10^{-7}$ m/s, and could therefore act as important pathways for escaping radionuclides as illustrated in case 4, see Figure 4–1. The distance between these subhorizontal fracture zones are, however, estimated to be about 700 m, so it should be possible to find a location for a KBS-3 repository where the distance to any subhorizontal fracture zone is large (some hundreds of meters). If, however, a subhorizontal fracture zone should be present in the vicinity of a deposition hole, the radionuclides have to migrate through about 0.4 m bentonite before entering a water carrying fracture that is connected to the subhorizontal fracture zone or migrate by diffusion through the rock between the bentonite and the fracture zone.

The transport in the disturbed zone surrounding the tunnel will be dependent on parameters like the Darcy velocity, the area available for surface sorption and sorption on the inner surfaces of the rock matrix. The water flow rate is determined by the hydraulic conductivity and the prevailing gradient. The hydraulic gradient is influenced by the fracture zone pattern in the far-field and is assumed to be on the order of 0.003 m/m at the 500 m level [*Pusch et al., 1991*].

Heat will be generated by the fuel in the canisters. The obtained thermal gradient may affect the water flow and the transport of radionuclides in the bentonite buffer as well as in the disturbed zones. The effect of this thermal gradient will, however, be largest for a "short" initial time period of some hundreds of years so the impact of the thermal gradient on the transport of radionuclides from canisters without initial defects is therefore considered to be insignificant.

Radionuclides migrating in the disturbed zone will be significantly delayed compared to the water velocity because of sorption on available fracture surfaces and diffusion into the rock matrix and sorption on the inner surfaces of the rock. The magnitude of these retardation mechanisms is to a large extent determined by the flow wetted surface per volume of flowing water. A larger flow wetted surface will give more retardation.

The transport from the disturbed zone and subhorizontal fracture zones through the far-field rock and to the biosphere is discussed in Section 4.3.5.

VLH

As in KBS-3,the use of a bentonite with a high initial water content or the relatively short time required for water saturation of unsaturated bentonite should minimise the risk for cementation of the buffer during homogenization at elevated temperature.

The water flow in the disturbed zone in a VLH repository is expected to be lower than in KBS-3 because of a smaller extension of the disturbed zone. This implies that the alteration of bentonite into illite will take at least as long time as in KBS-3, i.e. million(s) of years if the supply of potassium by water flowing in the disturbed zone is rate limiting assuming a concentration of potassium of 13 mg/l (Appendix 2). Conversion from sodium to calcium bentonite will increase the hydraulic conductivity in the bentonite barrier, but not to such extent that advective transport driven by the natural gradient will become significant compared to transport by diffusion.

The disturbed zone around the deposition tunnels are assumed to be of some importance for radionuclide transport also in the VLH concept. The transport path from a hole in a canister to the disturbed zone is illustrated in Figure 4–2.

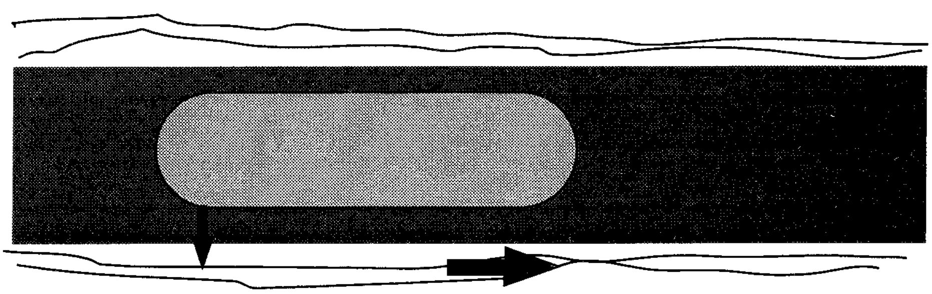

Figure 4-2. VLH. Transport pathway for radionuclides in the near-field.

The identified migration paths for the radionuclides are:

1: Diffusion through the bentonite into the disturbed zone around the deposition tunnel or directly into fracture openings in the deposition tunnel.

2: Diffusion through the bentonite into the disturbed zone around the deposition tunnel and transport from the disturbed zone through the rock to a subhorizontal fracture zone located close to the deposition tunnel.

It should be noted that the initial migration path of the nuclides in case 1 and case 2 is identical. In both cases the initial transport of the radionuclides must be diffusion through the bentonite barrier and subsequent migration into the disturbed zone. The thickness of the bentonite barrier is about 0.4 m, but water conductive 4th order fractures connected to the disturbed zone are expected to intersect the deposition tunnel every 4-8 m meaning that the migration distance in the bentonite will most probably be significantly longer than 0.4 m. The migration from the bentonite buffer into the disturbed zone will be affected by the transfer resistance at the interface.

Subhorizontal fracture zones have high hydraulic conductivities but a spacing as large as about 700 m. The long extension of a VLH repository might, however, induce difficulties to assure that the entire deposition tunnel is located far from any subhorizontal fracture zone. If the radionuclides should end up in subhorizontal fracture zones, as in case 2, they have to pass through the disturbed zone that circumvents the deposition tunnel and migrate by diffusion and/or advection in a fracture to the subhorizontal fracture zone.

MLH

As in KBS-3, the use of a bentonite with a high initial water content or the relatively short time required for water saturation of the bentonite should minimise the risk for cementation of the buffer during homogenization.

The water flow rate in the disturbed zone around the deposition tunnels in a MLH repository will be lower than in the disturbed zone around the drifts above the deposition holes for KBS-3 because of the smaller extension of the disturbed zone. On the other hand, if the comparison is made between the deposition tunnels for the MLH and the deposition holes for KBS-3, the disturbed zone around the horizontal deposition tunnels will probably be subject to larger water flow rates than the disturbed zone in the vertical deposition holes. The deposition tunnels for the MLH alternative are connected to the blasted access tunnels at both ends and can serve as a conductor between the larger tunnels, whereas the vertical deposition holes are "dead-end" constructions.The transport path from a hole in a canister to the disturbed zone is illustrated in Figure 4–3.

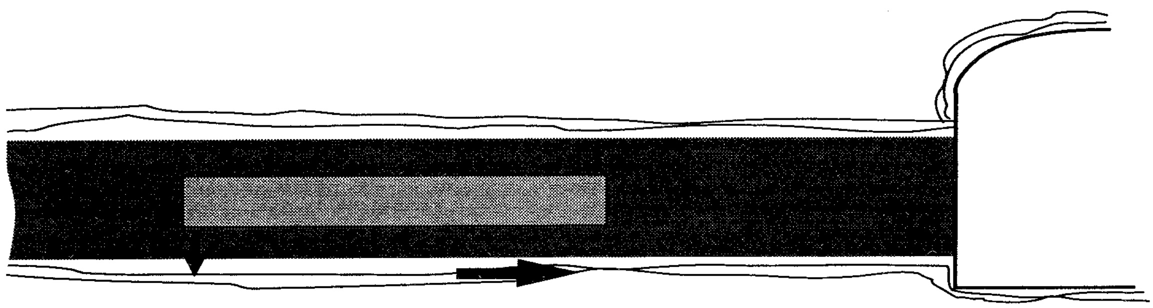

Figure 4-3. MLH. Transport pathway for radionuclides in the near-field.

The identified migration paths for the radionuclides are:

1 : Diffusion through the bentonite into the disturbed zone around the tunnel or directly into fracture openings in the deposition tunnel and transport away from the deposition tunnel in this fracture.

2 : Transport in the disturbed zone around the deposition tunnel to the disturbed zone around the access tunnel.

3 : Transport from the disturbed zone through the rock to a subhorizontal fracture zone located close to the deposition tunnel.

VDH

The canisters in the VDH concept will be surrounded by bentonite mud, see Section 3.5.3, with a thickness of about 0.15 m. It is, however, not reasonable to assume that the proposed deposition technique will guarantee that the canisters will be located in the central part of the deposition hole and thus be surrounded by an equally thick bentonite barrier in all directions. Radionuclides escaping from a failed canister might therefore have a shorter transport distance to the rock than 0.15 m.

Heat generated from the canisters will induce water to flow upwards, i.e. in the same direction as the deposition holes and the disturbed zone. The impact of the water flow due to the thermal gradient is largest for a "short" time period of some hundred(s) of years, but could influence the transport of the radionuclides since it can not be excluded that a large number of canisters will be initially damaged.

The about 5 m long canister in the VDH concept will be surrounded by bentonite mud having an initial hydraulic conductivity of $K=10^{-9}$ m/s. The canisters will be separated by a bentonite plug with an initial hydraulic conductivity of $K=10^{-11}$ m/s. The high hydraulic conductivity in the bentonite mud and the heat generated from the canisters might induce advective transport of water and nuclides within, at least, this "isolated" 5 m section. This advective transport within the bentonite mud might enhance the release rate if a fracture or fracture zone intersects the deposition hole over this distance.

4.3.5 Radionuclide transport in the far-field rock

The transport in the far-field includes the transport within the fractures and fracture zones found in the rock between the repository site and the biosphere. The initial migration in the near-field barriers is discussed in Section 4.3.4.

Flow within fracture planes

The water flow in crystalline rock have in several investigations been found to be very unevenly distributed. A minor part of the fractures seen in tunnels and boreholes carry water and only a few of the water carrying fractures are responsible for the largest parts of the observed water flow rates. It has also been found that the flow is located to certain pathways within the fractures. This has been noted from inspections of excavated tunnels where it can be seen that water emerges in narrow spots in fractures and fracture intersections [*Neretnieks et al., 1987*]. These observations together with results from tracer migration experiments in single fractures as well as in a local fracture zone [*Abelin et al., 1987, Abelin et al., 1990, Birgersson et al., 1992*] has lead to the development of the conceptual model of channeling. The idea is that the water flows in quite widely separated channels, which may extend for considerable distance without significantly intersecting other channels.

The actual nature of the flowpaths within the fractured rock will affect the radionuclide transport for several reasons. Firstly, the size of the contact area between the flowing water and rock surface is crucial for the diffusion into the rock matrix and for the sorption of dissolved spices on the rock surfaces. Secondly, the flow path connectivity is of importance for the residence time distribution and thereby for the dispersion of radionuclides.

Dispersion due to a variance in the water residence times is of great importance for the transport of radionuclides in fractured rock. The dispersion may give rise to a spreading of the concentration pulse and thereby lowering the maximum release rate for narrow peaks. However, the spreading may also lead to an earlier breakthrough, which may increase the release of radionuclides with a radioactive half-life of the same magnitude as the travel time, due to the smaller time available for radioactive decay.

Retardation mechanisms

The transport of dissolved radionuclides in the flowing water will be retarded in relation to the water velocity. This may be due to sorption on the solid surfaces, surface sorption, or due to diffusion of the radionuclides into the porous rock matrix, matrix diffusion. The diffusion into the matrix also gives access to the large inner surfaces of the rock which thereby can be utilized for sorption.

One mechanism that, could be of importance for radionuclide migration is the transport by colloids that potentially are present in the groundwater. Colloids might serve as an important transport vehicle for radionuclides since, whilst nuclides are sorbed on colloid particles, they will migrate with the flowing water without access to matrix diffusion [*SKI, 1991*]. However, a study by Allard et al. [*1991*] indicates that a fraction of dissolved radionuclides irreversibly sorbed to colloids, in amounts corresponding to colloids occurring in deep groundwaters, transported with the velocity of water does not seem to give high doses even in a case where all the leaking nuclides go to one well, despite that this fraction does not have the same opportunity to decay as the dissolved fraction has.

Surface sorption

It has been shown [*Neretnieks, 1987*] that for radionuclides with non-negligible surface sorption, the nuclide velocity in the rock will be independent of the linear velocity of the water in the fractures. The nuclide velocity will then primarily be determined by the water flux (Darcy velocity), the surface sorption coefficient and the contact area between the flowing water and the fracture surfaces. Surface sorption is a mechanism that has been validated in tracer experiments in the Stripa mine [*Abelin, 1986*]

Matrix diffusion

Granitic rock has in laboratory as well as in field experiments [*Skagius et al., 1982; Skagius and Neretnieks, 1986a, b, 1988; Skagius, 1986; Bradbury and Stephen, 1985; Bradbury et al., 1982; Bradbury and Green, 1985, 1986; Birgersson and Neretnieks, 1990*] been found to have a continuous system of microfissures between the crystals in the rock matrix. These micropores are filled with practically stagnant groundwater and can be accessed by molecular diffusion of radionuclides present in the flowing water in the fractures. The rate of uptake into the matrix will be influenced by the diffusivity, the sorption coefficient and in addition by the flow wetted surface. The latter is the fracture surface which the flowing water contacts as it flows through the rock. The larger this surface is the more of the nuclide can be "soaked" up by the rock matrix. At a later stage the radionuclides may diffuse out of the matrix back to the flowing water of the fracture. This effect gives an important retardation mainly for sorbing radionuclides. However, even non-sorbing nuclides will be retarded because they can diffuse in the porous rock matrix and thus access a large volume of stagnant water. The additional residence time while the nuclide resides in the matrix water may be several orders of magnitude larger than the residence time of the water flowing in the fractures.

Matrix diffusion and subsequent sorption onto the inner surfaces is by far the most important retardation mechanism for sorbing nuclides. It has been shown that the rock volume that can be accessed by diffusion during contact times of hundreds of years may have a considerably larger retardation effect than surface sorption [*Neretnieks, 1980*].

The retardation factor will not be constant, but will increase with time, since the penetration depth will increase with increasing contact time. However, the penetration depth will be very small for strongly sorbing nuclides, but in this region the concentration of sorbed radionuclides will be very high and the retardation effects are still formidable.

KBS-3

Radionuclides escaping from the canisters and the near-field of a repository will be transported through the far-field by the mobile water in fractures and fracture zones. The repository will be located in rock where the flow of water is very limited, but the water from a repository will eventually reach more conductive features, the fracture zones. If the geology and hydrogeology of larger rock volumes are considered, see Chapter 2 and Appendix 6, it is obvious that the most important water flow paths in the far-field are the existing fracture zones of different orders. These fracture zones might be more or less connected with each other as well as with the biosphere receptors.

Before the nuclides emerge into a fracture zone intersecting a repository tunnel they have to migrate a distance within the disturbed zone around the deposition tunnel. The number of different order fracture zones that are expected to intersect a repository and an estimate of the respect distance to these zones is dependent on the geometrical layout of the repository, see Appendix 1.

A possible transport path in the near-field rock, described in Section 4.3.4, is migration of the nuclides to a subhorizontal fracture zone in the vicinity of the deposition hole. Subhorizontal fracture zones are found with a spacing as large as about 700 m, but could be important pathways for escaping radionuclides because of their hydraulic conductivity which is on the order of $K=10^{-7}$ m/s compared to the hydraulic conductivity in the disturbed zone around the deposition hole which is orders of magnitude lower.

The migration distance for radionuclides escaping the near-field barriers will be at least 500 m in the far-field rock. The transport through the far-field will reduce the rate of release to the biosphere, compared to the rate of release from the near-field, by retarding the nuclides and thereby allowing them to decay. Far-field transport may also lower the concentrations of radionuclides at the release points by dilution, thereby reducing the dose consequence of using the contaminated groundwater.

A ramp and shafts will extend from the surface to the repository level. After deposition of the canisters these shafts/ramp will be sealed using a backfill consisting of bentonite or a sand/bentonite mixture. This backfill will have a lower hydraulic conductivity than the surrounding rock and should therefore not constitute any important pathway for escaping nuclides. The shafts/ramp will, however, be surrounded by a disturbed zone with an high axial hydraulic conductivity that, unless plugging is successfully performed, could act as a potential pathway for nuclides.

VLH and MLH

The description of the transport in the far-field given above for the KBS-3 concept is valid also for the VLH and MLH concepts since all these repositories are proposed to be located at the same depth in the bedrock. The larger extension of the VLH repository can lead to an increased number of intersecting fracture zones and to difficulties in avoiding subhorizontal fracture zones.

VDH

The mechanisms described in this section for transport in fractured crystalline rock have been found to be present in rock relevant for the depths corresponding to the KBS-3, VLH and MLH concepts. Even if there is a general lack of information at depths relevant for the VDH concept, there is no reason to believe that these mechanisms should not be present.

The canisters are proposed to be located at 2000–4000 m depth in the VDH concept and it is known from measurements in deep boreholes, for example Gravberg–1, that the hydraulic conductivity and frequency of water conductive fractures decrease with increasing depth. Measurements have also shown that the salinity increases with depth and is typically 100–300 g/litre in measured holes (one in Sweden two in Russia and one in Ukraine) at the level proposed for a VDH repository compared to about 10 g/litre at the 500 m level. The increased salinity at large depths gives a higher density of the water. For the measured gradients this has been shown to be [*Claesson, 1992*] a very efficient barrier since this density gradient prevents the water at large depths to be mixed with more shallow water. Radionuclides escaping failed canisters at large depths would then not be transported up into more shallow waters and thus be prevented from emerging in the biosphere.

The deposition holes will be sealed using bentonite, concrete and asphalt but there will be a disturbed zone around the entire lengths of the boreholes. This disturbed zone might act as an transport path for escaping nuclides. Plugs with slots blocking these transport paths is one engineered possibility to overcome this disadvantage.

4.3.6 Radionuclide transport in biosphere

Groundwater will carry radionuclides to primary receptors in the biosphere. These receptors are site-dependent and also dependent on the time of release. Since radionuclides most likely not will be released to the biosphere prior to the next glaciation period, the uncertainties about the state of the biosphere at the time of release is large (see Section 4.2.6). Therefore, the biosphere transport is only discussed in terms of typical primary receptors and potential dilution of radionuclides in these receptors.

KBS-3

One potential primary receptor is a lake. Because of the quadrangular extension of the repository it seems possible that all the main water bearing discontinuities intersecting the repository will discharge all their water into the lake. Nuclides in the discharged water are diluted in the water in the lake. A similar situation could be expected for a sub-seabed or near-coastal location of the repository except that the discharge occurs into the sea.

If a well is drilled in the discharge area of the repository it cannot be ruled out that the well is placed in a fracture zone to which discontinuities intersecting the repository discharge their water. The large amount of radionuclides escaping from the repository may then be collected in the well. However, it is possible that not only water from the discontinuities intersecting the repository is flowing in the fracture zone, but also water from other discontinuities in the rock. This, and withdrawal of more surficial water into the well during pumping will result in a dilution of the radionuclides.

VLH

Because of the large horizontal extension of the tunnels in the VLH concept, 4.5 km, it is not very likely that all radionuclides escaping from the repository will end up in the same water reservoir (e.g. lake or well) in the biosphere, as in KBS-3. One exception could be a sub-seabed repository which still is located beneath the bottom of the sea at the time of release. A distribution of the radionuclides to several receptors in the biosphere would be advantageous in terms of lower individual dose, but disadvantageous because larger areas and a larger population will be exposed to escaping radionuclides.

MLH

The biosphere is equal to that described for KBS-3 above.

VDH

The number of discontinuities intersecting each hole in VDH is uncertain and thereby the potential transport paths in the geosphere. However, water conductive zones are expected to be present also at depths between 2 and 4 km. In addition, the disturbed zone around the hole is a potential conductor giving access to additional discontinuities at shallower depths. If the water flowing in these discontinuities ever reach the biosphere the location of the discharge will probably not be the same for all discontinuities. This, together with the fact that the repository contains 35 holes with a distance of 500 m between the holes implies that radionuclides escaping from the repository are distributed among several primary receptors in the biosphere such as lakes or wells.

4.4 Intrusion Scenario

Human actions that result in intrusion and thereby exposure to radiological risk could be either accidental or deliberate. The accidental intrusion conditions that the information about the existence or exact location of the repository has been lost. Since the content and location of the repository will be thoroughly documented it would take major catastrophes or glaciations for this knowledge to be lost. The detailed documentation of the repository should prevent future decisions of intrusion based on incomplete or missing background information. The possible events that could cause an accidental intrusion into the repository are mining activity or other major excavation for example the construction of underground dwellings, drilling for water, geothermal energy or other purposes. A willful intrusion would most likely aim at recovering the copper or the fuel waste. The decision to perform such willful intrusion activity can probably not be prevented and it must be allowed for future generations to make such decisions as well as a responsibility for them to evaluate the safety of their actions.

KBS-3, VLH and MLH

The activity that is considered most likely as a cause of accidental intrusion is a well for all the 500 m alternatives.

VDH

No accidental or deliberate intrusion for the VDH concept is likely to happen.

4.5 Glaciation Scenario

During the next 100 000 years glaciations are expected to cover Scandinavia. Several thousand meters of ice will cover the earth surface and cause large rock movements in the geosphere. It is conceivable that new faults will be formed during a glaciation but most likely movements will occur at the already existing major fault zones. The rock movements will be of smaller magnitude at larger depths, as for the VDH concept compared to the 500 m alternatives. On the other hand, for the VDH concept it is not likely that deposition of canisters close to existing fault zones can be shown to be avoided with present geo-investigation technology.

The scenario is based on the assumption that the result of the glaciations in the repository environment will be a change in the water flow rates in fracture zones due to changes in the hydraulic gradients for the KBS-3, VLH and MLH concepts. For the VDH concept damage to canisters due to rock movement is assumed in addition to changes in water movement. Changes in the groundwater composition at repository level in KBS-3, VLH and MLH can occur due to oxygen rich water that is forced down during the glaciation.

5. COMPARISON OF PERFORMANCE AND LONG-TERM SAFETY

5.1 General

The evaluation of the long-term safety of radioactive waste repositories can be based on dose limit criteria. These are usually given as limitations in individual dose. However, for deep repositories for high level waste, the safety assessment must be based on predictive modelling of the performance over very long time. There are obvious uncertainties associated to such modelling and the derived doses should rather be seen as indications than as predictions. The uncertainties concern both the possibility to predict the evolution of the repository, e.g. life time of barriers, as well as the difficulties in predicting the occurrence of future events with a detrimental effect on the repository performance, e.g. faulting. Furthermore, human habits and environmental conditions may change over relatively short time scales. In a comparison of the long-term safety of different repository concepts, these uncertainties must be considered in addition to the predicted dose limits.

5.1.1 Procedure

In this study the first step in the comparison of the long-term safety of the repository concepts has been to specify design parameters for each concept, such as repository depth and dimensions, and type of material and dimensions of the different engineered barriers. Based on this information, the initial and long-term performance of each barrier in a concept as well as effects of interaction between barriers are qualitatively evaluated. The sensitivity of the performance of the barriers to future events with a potential detrimental effect is also qualitatively assessed. One such event could be faulting as a result of glaciation. Furthermore, the possibility and consequences of human intrusion is addressed for each concept, see Section 4.4.

In the next step the individual barriers within the concepts are compared, see Section 5.2. The purpose of the analysis of the barrier performance is to get a qualitative estimate of the relative importance of the different barriers for the long-term safety within each concept, as well as to identify differences in barrier performance between the different concepts. The relative importance of a barrier within a concept for the long-term safety is determining the importance of an identified difference between the concepts. For example, if the main difference between the concepts is found in a barrier of less relative importance for the total safety, this difference is given a low weight in the integrated comparison. In addition, a qualitative judgement of the uncertainties associated with the expected barrier performance is made.

Finally a qualitative comparison between the repository systems has been performed based on a set of comparison criteria, see Section 5.3. However, to make the comparison complete, differences between the concepts in dose to man should also be addressed . This would require a quantitative estimate of the integrated performance of each concept (or a subset of the concepts) for a reference scenario as well as for other defined scenarios covering future rare events. The uncertainties involved in the doses calculation should also be addressed.

5.1.2 Areas/activities considered in the comparison of the individual barriers

The considered areas are those usually treated in safety assessment of a final repository: the near-field including the engineered barriers and the disturbed zone, the far-field and the biosphere, see Figure 5–1. For each area the *function/effects*, *characteristics*, *technical factors*, and *potential differences* are identified.

Function/effects lists the desired function or the expected effects of the area/barrier related to long-term safety.

Characteristics defines the properties/parameters of importance for the functions/effects and gives a guidance to what information is needed in order to evaluate the long-term safety.

Technical factors are identified features in the repository concept that may have an influence on the characteristics and thereby on the long-term safety.

Potential differences list the features which are different between the repository concepts in respect to long-term safety. In this part no evaluation is made of the magnitude of these differences or of differences in the combined effect of all areas/barriers. In addition, uncertainties associated with features and processes which may influence the desired barrier function are mentioned. The potential differences in barrier performance and their influence on the long-term safety will constitute the basis for the final ranking of the repository concepts.

5.1.3 Comparison criteria in the evaluation of repository systems

In order to perform an integrated comparison between the repository systems a set of comparison criteria must be set up. In this section a set of criteria has been defined based on internationally developed standards and guidelines. The evaluation of the long-term safety of a repository concept is usually based on dose limit criteria. There are, however, also other aspects which should be included in the evaluation of long-term safety and thereby also be considered in the comparison between different concepts. These are discussed below in addition to the dose limit criteria.

Dose limit criteria

The radiological consequences of releases due to "gradual" processes are usually evaluated by assessing the individual dose to a member of a critical group. However, for deep repositories the maximum doses may arise at times far into the future. Despite the obvious difficulties to estimate doses in the far future, no general time cut-off criteria is used in safety assessments. The doses calculated for the long-term period should not be considered as predictions, but rather as indications of what doses could be with a present day ecological and social system.

Possibility of validation

Despite the generic uncertainties in predictions of the long-term safety it is accepted that technical and scientific techniques can be used to indirectly demonstrate the repository safety. However, the models used in a safety assessments must be validated as far as possible [*IAEA, 1989*]. The validation shall give a reasonable assurance that the model is applicable to the specific disposal system. The degree of validation needed for a model will depend both on to what degree it influences the safety, as well as on the amount of scientific and technical experience available in the area. As an example, far-field migration models will be more in need of validation than models of some man-made structures for which experience exist [*Andersson et al., 1990*].

The need for validated models in the performance assessment put requirements on the technical solutions in the repository design and also on the site selection process. The technical designs chosen should not strive only for maximum safety, but should also strive for systems which are possible to validate. The possibility of validation may also vary between sites, however, this is not taken into consideration in this study.

Multiple barrier principle

According to the IAEA Technical Criteria [*IAEA, 1989*], repositories for high level waste should be designed on a multiple barrier principle, i.e. the repository system should be made up of a system of natural and engineered barriers that in some ways are redundant. Thus the performance of the system will depend on the *total* system rather than the performance of a single isolating or retarding mechanism or process. In a comparison between different repository alternatives, the evaluation of the safety of the individual mechanisms or processes must therefore be combined with an evaluation of to what degree the overall safety depends on the function of them. A repository design may include a barrier with a very high level of safety, but should that barrier fail, the overall safety of the repository may be low.

Scenario evaluation

One way to deal with the uncertainty in predictions is to define a set of scenarios that will cover a range of possible future evolutions of the repository system. The scenarios may illustrate events with a high probability, e.g. glaciations, as well as events with a low or uncertain probability, e.g. major faulting or direct human intrusion in the repository. The repository design should be such that it has a high degree of safety for various scenarios. In a joint report made by the Swedish and Swiss authorities [*Andersson et al., 1990*], a risk limit has been proposed as a complement to the dose limit, for the evaluation of single rare events. They propose that the total risk from a single event from one source should not exceed 10^{-7} for any one year, and that the risk limit may be applied to events with a frequency of occurrence in the range 10^{-7} - 10^{-3} per year.

Retrievability and institutional control

In the IAEA Safety Principles no requirements are put on the retrievability of the waste after repository closure [*IAEA, 1989*]. In the report prepared by the Swedish and Swiss authorities [*Andersson et al., 1990*] it is concluded by IAEA that in the context of disposal there are no requirements that the disposed waste should be subject to retrievability. On the other hand an ethical principle would be not to construct a repository in a way that would unnecessarily hinder future generations from making remedial actions. This principle has also ben considered in PASS. It is further concluded that there should not be any scientific need for environmental monitoring after the repository is closed, although a monitoring program may be required from a public point of view.

Comparison criteria

In this study a set of comparison criteria for the integral comparison of the repository concepts are set up from the general safety principles and technical requirements discussed in previous subsections. These are:

1. The capability to isolate the waste to such a degree that the predicted doses do not exceed the limits.

2. How the isolation capability depends on individual barriers, i.e. multiple barrier principle.

3. The possibility of validating the performance of the repository, i.e. uncertainties in the qualitative and quantitative analyses of barrier performance.

4. The capability to isolate the waste in case of rare events.

5.2 Comparison of individual barriers

The assessment system for the evaluation of the performance and long-term safety is given in Figure 5–1, and in somewhat more detail in Appendix 5. In this section the areas/ activities going into the assessment system and the comparison of the individual barriers are first presented. Hereafter, considered topics and the potential differences in barrier performance between the concepts are presented.

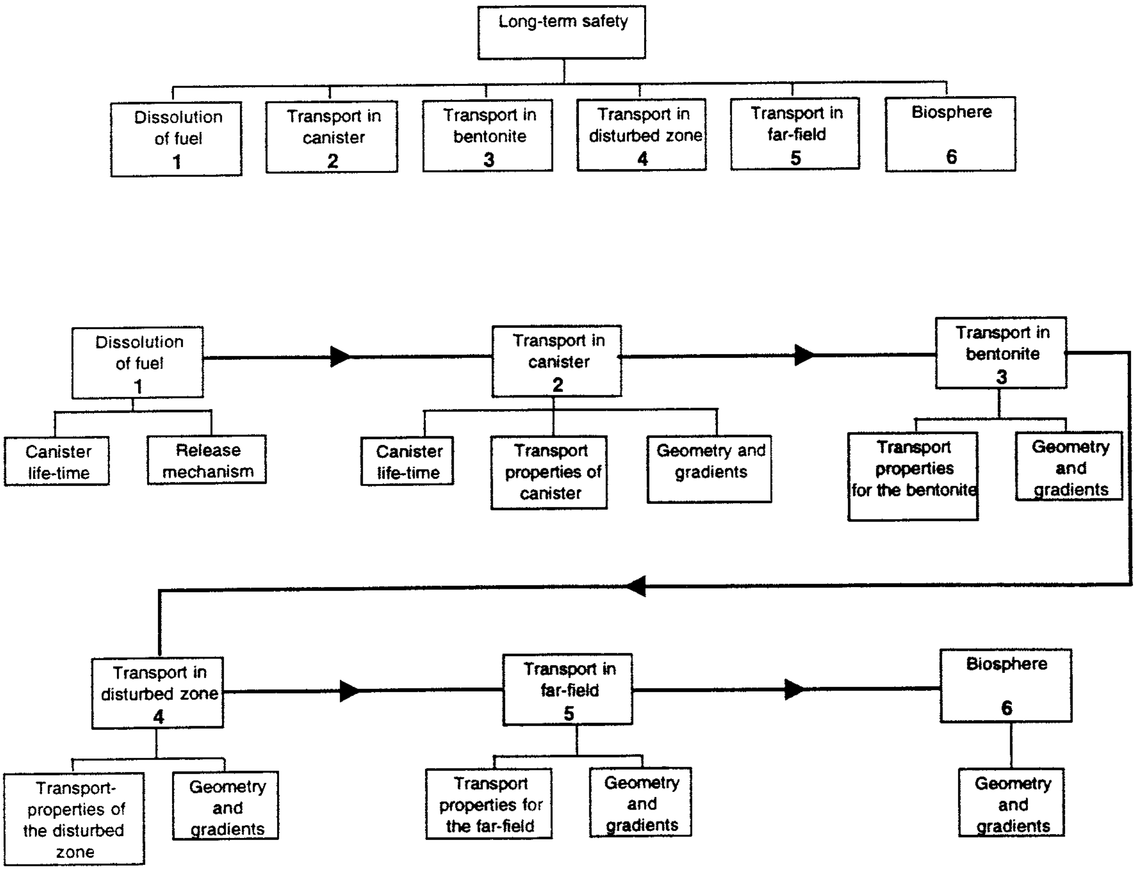

Figure 5-1. Description of the assessment system.

5.2.1 Canister

The canister is defined as the barrier surrounding the fuel matrix and thereby includes the function of a canister filling material inside the canister.

Function/effects

The main function of the canister is to isolate the spent fuel and thereby the radionuclides from the environment for long-term periods. Therefore the canister lifetime is an essential parameter for predictions of long-term safety. When a canister has failed, the fuel matrix, possible filling material and the canister itself will still offer a transport resistance for the radionuclides leached from the fuel.

Characteristics

The characteristics which will determine the canister life time are listed below:

- geometry
- heat conductivity
- initial canister integrity
- mechanical stability, external influence
- mechanical stability, internal pressure
- corrosion resistance.

In addition characteristics which will determine the radionuclide release from the spent fuel and the canister are listed below:

- release mechanisms
- chemical and physical condition of fuel
- fuel dissolution rate
- oxidant production
- solubility limits
- geochemical environment
- free water volume in canister
- canister failure mode.

Technical factors

The technical factors which will have an influence on the evaluation and prediction of canister characteristics are listed below:

- canister design
- canister material
- filling material
- waste loading
- fuel burn-up
- quality assurance from encapsulation
- protection during operation/transport.

Potential differences in canister life time

The canister life-time is of importance for the long-term safety mainly in terms of radionuclide content in the fuel at canister failure. The canister life-time is dependent on the properties of the canister and the surrounding barriers, which therefore are used as a basis for comparison. The aspects considered in the comparison of the canister life-time in the different concepts are:

- risk of remaining manufacturing defects after quality control
- risk of creating canister damages during deposition operations without observing it
- sensitivity to failure by corrosion or mechanical impact due to canister material and design
- capability of the surrounding bentonite buffer to protect the canister mechanically as well as to maintain a chemical environment which minimise canister corrosion
- sensitivity to failure by corrosion or mechanical impact due to repository design.

Remaining manufacturing defects

Manufacturing defects that remain undetected during the quality control are most likely very minor such as a small pore in the weld. The probability of such defects is assessed to be very low in all concepts and no clear difference between the concepts in this respect is identified.

Canister damage during deposition

The large risk of creating damage to the canister during deposition and the difficulties in performing visual control and retrieval after deposition is clearly disadvantageous in the VDH concept compared to the other concepts. No obvious difference between the KBS-3 the VLH concept and MLH concept is identified.

Sensitivity to failure due to canister design

In both the KBS-3/MLH and the VLH canister the internal void is assessed to be large enough, if a granular filling material is used, to ensure that helium generation inside the canister not will result in a pressure increase that may rupture the canister.

The sensitivity to failure due to outer mechanical impact is not expected to differ between a KBS-3/MLH and a VLH canister as long as the inner, pressure retaining steel canister is intact. The larger VLH canister is probably more sensitive to mechanical load when corrosion of the inner steel canister is initiated.

The canister material, copper-steel, and the thickness of the copper layer is similar in KBS-3/MLH and VLH, but the inner steel canister is twice as thick in a VLH canister compared to a KBS-3 canister. Theoretically this would mean that a VLH canister has somewhat longer life-time if the failure is due to corrosion. However, the expected time-scale of millions of years for corrosion to penetrate the outer copper layer and the uncertainties associated with the mechanisms of importance for the corrosion rate overshadow this difference in design. No significant difference in corrosion behaviour because of difference in canister design is therefore expected between a KBS-3/MLH and VLH canister.

The sensitivity to failure because of canister design is expected to be larger for a VDH canister compared to the other canisters. The interior of the titanium canister is filled with concrete containing water and both external and internal corrosion is then possible. Furthermore, the thickness of the titanium is smaller than the copper shell in a ACP-canister and the possibility of creating small defects initiating localized corrosion is larger because of the difficult handling during deposition. In addition, the risk of hydrogen embrittlement of titanium and the potential pressure increase inside the canister because of helium and hydrogen formation will make the VDH canister more sensitive to mechanical failure.

Protection by surrounding bentonite buffer

In the comparison it is assumed that the sodium bentonite to be used as a buffer in the 500 m level repositories is quite similar what concerns pre-treatment and composition, and that the buffer is deployed in such a manner that similar properties are obtained after water saturation. Because of this similarity in initial bentonite properties and thickness around the canister, as well as in the composition of the groundwater in contact with the bentonite and the canister material no major difference in properties of importance for the long-term mechanical support of the canister is expected between KBS-3, VLH and MLH. Neither are significant differences foreseen in long-term properties of potential importance for copper corrosion, such as amounts of entrapped oxygen, content of organics and sulphides, transport resistance to corrodants, pH-buffering capacity, and thermal conductivity.

In VDH, the initial properties of the bentonite buffer as well as the composition of the groundwater and the expected maximum temperature level differs from the 500 m level repositories. The risk of cementation due to silica and calcite precipitation, and thereby loss of plasticity of the buffer, is potentially somewhat higher in VDH because of higher temperature and higher salinity of the groundwater. The thickness of the bentonite buffer in VDH is also smaller than in the other concepts which would make the buffer and canister more sensitive to small rock movements. It is also believed that it is difficult to ascertain that all canister are surrounded by the high density buffer material in the deposition zone because of the complex operation to lower down canisters and bentonite and to add bentonite to sections with breakouts in the holes. What concerns the long-term properties of importance for corrosion of the canister, the transport resistance in the bentonite for corrosive agents is probably lower than in the other concepts, and potentially none at all if the bentonite barrier is made incomplete and the canister is in direct hydraulic contact with the rock.

Sensitivity to failure due to repository design

The risk for rock movements due to the design of the repository is potentially higher in KBS-3 than in VLH and MLH. The combination of disturbances from the tunnel blasting and the drilled deposition holes may increase the risk for movements of the rock around the upper parts of the deposition holes in KBS-3.

In VDH, it is most likely that instabilities in the hole appear during the drilling phase [*Juhlin and Sandstedt, 1989*]. However, if stable borehole breakouts are formed, the stress magnitude can increase which in time may result in rupture. The consequences of a rupture after deposition of canisters are uncertain, but it cannot be excluded that canisters are damaged.

Conclusion

In summary it can be concluded that no major difference in the life-time of a canister is expected between the 500 m level concepts because of the similarity in canister material and design as well as in the environment surrounding the canister. Potentially, the life-time of a VLH canister with an initial defect is shorter than a KBS-3/MLH canister with an initial defect because of a smaller mechanical resistance once the inner, pressure retaining steel canister is exposed to corrosion. However, the risk for deposition of a canister with a small defect is assessed to be very small in both concepts.

The potential life-time of a VDH canister is assessed to be short compared to the other canisters mainly because the integrity of a canister in the VDH concept cannot be guaranteed after deposition. Furthermore, the potential for events after deposition that jeopardize the canister integrity seems to be larger in this concept although the uncertainties are large.

Potential differences in the radionuclide release from the canister

The entities of importance for the radionuclide release rate and total release from a failured canister are summarised into the following comparison criteria:

- canister life-time
- nuclide concentration inside the canister
- transport resistance in canister
- release mechanism.

Criticality can not be ruled out for un-filled KBS-3-, MLH- and VLH-canisters but in VDH the amount of fuel is such that no risk for criticality exist [*Lönnerberg, 1992*]. Therefore the comparison is based on the presumption that the canisters are filled in order to eliminate the risk for criticality after canister penetration.

Canister life-time

As stated above, a considerably shorter canister life-time is expected in the VDH concept compared to KBS-3, VLH and MLH with the consequence that more short-lived radionuclides still are present at the time of canister failure.

Nuclide concentration

The nuclide concentration inside the canister after canister failure and water penetration is dependent on the amount of fuel in the canister, the amount of water in contact with the fuel and the chemical conditions prevailing inside the canister.

Theoretically, the larger ratio internal void to amount of fuel in a VLH canister compared to a KBS-3/MLH canister can result in approximately 2 times lower concentration of non-solubility limited radionuclides. No difference in the concentration of solubility limited nuclides is expected, because of the similarity in chemical conditions inside the canisters.

A comparison of the ratio internal void to amount of fuel in a VDH and a KBS-3 canister shows that the concentration of non-solubility limited nuclides in a VDH canister could be twice the concentration in a KBS-3 canister. Because of the high pH maintained by the concrete in a VDH canister, the concentration of solubility limited radionuclides is expected to be lower than in a ACP-canister provided that there are no major differences in redox conditions inside the canisters. The large redox buffering capacity achieved by the presence of steel in a ACP-canister will probably maintain reducing conditions inside the canisters. The redox buffer capacity in a VDH canister is uncertain, but will probably be lower than in a ACP-canister. If oxidizing conditions are developed in a VDH canister as a result of radiolysis, the positive effects of a high pH on solubilities of radionuclides may diminish in the comparison with the other canister types.

Transport resistance

The material inside the canister will constitute a transport resistance to dissolved radionuclides by restricting the pathways available for nuclides to move from the fuel surface to the hole or break in the canister, and by acting as a sorbent for the nuclides. In this respect there should be no difference between KBS-3/MLH and VLH canisters as long as the canisters are filled with the same type of material.

The created hole or break in itself also constitute a transport resistance for escaping nuclides. A very small hole or a low porosity of potential corrosion products in the hole may totally determine the nuclide release rate from the canister. In this respect there is a potential difference between a KBS-3/MLH and a VLH canister. Because of the larger sensitivity to mechanical impact for a VLH canister when corrosion of the inner steel canister is initiated, the risk for a larger hole or break to be created is assessed to be higher for a VLH canister.

The transport resistance inside a VDH canister is probably higher than inside a copper-steel canister filled with an inert material mainly because of the high sorption capacity of the concrete. Steel corrosion products in a ACP-canister may potentially be good sorbents, but the uncertainties are large and it is therefore difficult to take credit to this effect in a comparison. The disadvantage of the copper-steel canister with respect to sorption capacity may diminish if the canister is filled with a sorbing material.

What concerns the size of the hole or break, it is probably of less importance as a transport resistance in a VDH canister compared to the other canisters since the canister may be severely damaged after deposition.

Release mechanism

Radionuclides may be released from the hole or break in the canister by diffusion, by advection, or with water displaced by gas. The potential long-term changes in the hydraulic properties of the bentonite surrounding the canister in KBS-3, VLH and MLH are not expected to be that large that advection becomes important compared to diffusion. Thus, the dominating release mechanisms from these canisters are diffusion and possibly also displacement by gas.

Steel corrosion and gas formation in a KBS-3 and VLH canister will most likely restrict both displacement of water containing nuclides and diffusion of nuclides out through a hole or a break located in the uppermost part of the canister. The most disadvantageous location of the hole/break is in the lowest part of the canister as positioned in the deposition hole/tunnel because this would allow the total amount of water inside the canister to be expelled by gas, and gas inside the canister would not restrict nuclides ability to escape by diffusion. In this respect, the vertical position of the canister in the deposition hole as in the KBS-3 concept is more favorable than the horizontal in the VLH and MLH concept for the following reasons. Firstly, the hole/break in a KBS-3 canister due to an initial defect in the weld will always be located in the highest positioned part of the canister while such a hole/break in a horizontal canister may be located in the lowest positioned part. Secondly, it is believed that even if the canister initially is intact, the weld constitutes the part of the canister where localized corrosion is most likely initiated. Thirdly, the fact that the main corrodant sulphide is supplied by the bentonite buffer and backfill, which to a large extent is found above the canister, and by the groundwater, which mainly flows in the disturbed zone around the tunnel above the canister, further supports the higher probability of a localized corrosion attack in the top part of a KBS-3 canister. In VLH and MLH, no such preferential part of the canister exposed to corrosion is identified since the corrodant sources, bentonite and groundwater, are evenly distributed around the canister. Figure 5–2 illustrates the difference between a horizontal and a vertical placement of the canister with a penetration of the canister located at the weld.

In similarity to the other canisters the release of nuclides from a VDH canister may take place by diffusion and with water that is displaced by gas. However, the uncertainties in the actual initial conditions after deposition, such as degree of damage to the canister and the extent to which the canister is surrounded by bentonite in the deposition zone, also introduce uncertainties what regards the release mechanisms. This is considered to be a drawback for the VDH concept in comparison with the other concepts.

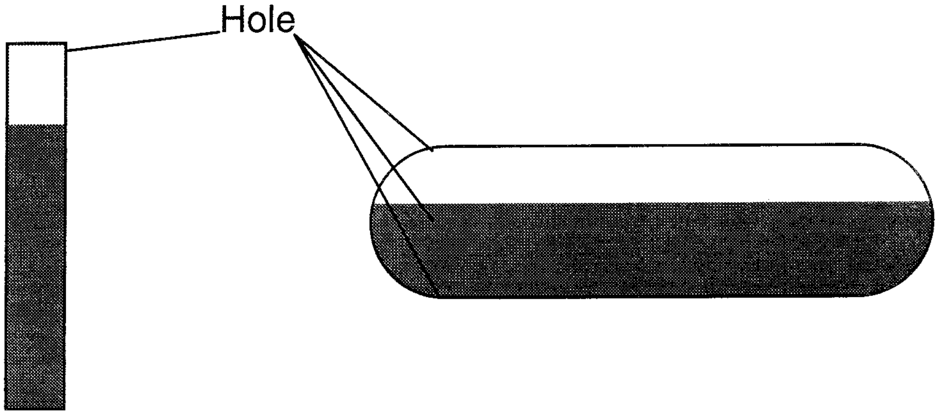

Figure 5-2. Vertical and horizontal placement of canisters.

__Conclusions__

In summary it could be concluded that the short life time and the risk of a rather severe damage to the canister may result in an earlier release and higher release rate of non-sorbing radionuclides from a canister in the VDH concept compared to the other concepts. The release of sorbing nuclides will also start earlier, but potential differences in release rates between the concepts are difficult to assess.

The horizontal placing and the higher sensitivity to mechanical impact of a corroded canister in the VLH concept may lead to a higher release rate and also, in case of an initially defect canister, in a somewhat earlier release compared to the KBS-3 concept.

In the MLH concept the same canister as for the KBS-3 concept is proposed, the only difference is the horizontal placing.

5.2.2 Bentonite buffer

The buffer material is here defined as the material surrounding the canister in the deposition hole or deposition zone.

Function/effects

The main function of the buffer material is to provide a mechanical support and to protect the canister from rock movements. In addition the buffer will act as a hydraulic barrier and restrict the water flow near the canister. The buffer will thereby offer a transport resistance for aggressive species in the groundwater as well as for radionuclides released from the canister. Other effects are that the chemical environment nearby the canister will be influenced by the buffer material, the buffer offer a low heat transfer resistance and that existing fractures in nearby rock may be partly sealed by the buffer material.

Characteristics

The characteristics determining the function of the buffer are listed below:

- geometry
- gradients, (hydraulic, thermal and gas)
- swelling ability
- plasticity
- permeability
- diffusivity
- sorption properties
- geochemical environment
- mechanical stability
- heat conductivity
- chemical stability
- redox capacity.

Technical factors

The technical factors which will have an influence on the evaluation and prediction of buffer characteristics are listed below:

- bentonite quality (properties, additives, water content)
- emplacement technology
- quality assurance
- long-term properties, (physical, chemical and thermal)
- influence of casings.

Potential differences in protection by surrounding buffer

The comparison of potential difference in protection offered by the surrounding buffer of the canister has already been treated in Section 5.2.1.

Potential differences in the radionuclide release from the bentonite buffer

The importance of the bentonite buffer as a barrier for radionuclides released from the canister is defined by its physical and chemical properties and by the geometry of the buffer. In addition, the groundwater flow situation around the buffer is of importance for the rate with which nuclides are released from the buffer. In the comparison these aspects are considered in terms of possible transport paths through the buffer and transport resistance in the buffer.

Transport paths

The shortest transport path through the buffer in KBS-3, VLH and MLH is radially out from the canister. In this respect the concepts do not differ since the thickness of the buffer in this direction is similar. However, this is the only transport path in VLH and MLH, but in KBS-3 longer paths are also possible since radionuclides can migrate upwards from the top of the canister through the buffer and backfill in the top part of the deposition hole and possibly also through the backfill in the tunnel.

The only transport pathway for a nuclide escaping from the canister in VDH is radially out through the buffer. The thickness of the buffer is, however, smaller in VDH than in the other concepts. Furthermore, it is very difficult to ascertain that the canisters will be surrounded by equal amounts of bentonite in all directions after deposition in VDH. In the extreme case parts of the canister may be in direct contact with the rock.

Transport resistance

In both KBS-3, MLH and VLH degradation of the bentonite is not expected to be so large that groundwater flow through the barrier will become significant. Displacement by gas of water containing nuclides may contribute during an initial time period but diffusion will be the dominating transport mechanism in the long-term perspective. Because of the high transport resistance in the buffer, the rate with which water could be displaced is low in all concepts and results in a release rate of nuclides of the same magnitude as the release by diffusion (Appendix 4).

The pore volume and the sorption capacity in the bentonite material will delay the nuclide transport and thereby reduce the release rate of short-lived radionuclides. The sorption properties are expected to be the same, but a canister in VLH is surrounded by 50% more bentonite on a volume basis and the capacity to retard the nuclides is then correspondingly higher. However, in KBS-3 the sand/bentonite backfill in the uppermost part of the deposition hole and in the tunnel constitute an additional, potentially large, capacity for retardation of nuclides migrating upwards through the deposition hole.

The additional resistance which lies in the diffusional transfer of nuclides from the buffer to groundwater flowing in the disturbed zone in the rock outside the buffer is dependent on the contact area and contact time between water and buffer. The similarity in geometry of the buffer surrounding the canister, but the expected lower hydraulic conductivity in the disturbed zone around the deposition hole in KBS-3, indicates that this transfer resistance is somewhat higher for radionuclides released to the disturbed zone around the deposition hole in KBS-3 than in VLH and MLH. On the other hand, the release of the rock stresses close to the tunnel in KBS-3 may result in larger apertures of fractures intersecting the uppermost part of the deposition hole compared to the apertures of the features in contact with the bentonite buffer in VLH and MLH. However, considering the uncertainty in actual water velocity as well as in contact length and area between groundwater flowing in the disturbed zones and the buffer in the two concepts it is not possible to postulate any difference of importance without calculations.

Compared to the KBS-3, VLH and MLH concepts both the transport resistance in the buffer and the resistance in the diffusional transfer from the buffer to the groundwater flowing in the disturbed zone in the rock outside the buffer in VDH could potentially be lower. The hydraulic resistance of the buffer is already initially lower and the higher salinity of the groundwater as well as the high pH maintained by the concrete in the canister may further reduce the hydraulic resistance as a result of bentonite alteration. In addition, failure in centering the canister in the hole during deposition may, in the extreme case, nearly short circuit the bentonite buffer. Furthermore, the direction of the thermal gradient coincides with the main direction of the hydraulic conductivity in the disturbed zone around the hole which may result in high water velocity in the disturbed zone and low resistance to the uptake of nuclides by this water. In addition, it cannot be excluded that advective transport may be significant in parts of the buffer because of the combination of high hydraulic conductivity and thermal gradient. However, the uncertainties associated with the performance of the buffer are large and the magnitude of the transport resistance in the buffer cannot be evaluated without a quantitative analysis of the VDH near-field.

Conclusions

No significant difference between KBS-3, VLH and MLH is expected what concerns the bentonite buffer acting as barrier to radionuclides released from the canisters, except for the possibility of a large sorption capacity and pore volume accessible for retardation of nuclides migrating upwards from the canister and further into the tunnel backfill in KBS-3.

In VDH, the buffer is expected to be less good as a barrier because the initial barrier properties are not as good as in KBS-3, VLH and MLH, and because the quality of the barrier might be inferior if the hole is irregular. In the extreme case short transport path from the canister to the rock could develop in the bentonite buffer.

5.2.3 Near-field rock

The near-field rock is defined as the host rock disturbed by the excavation and presence of a repository.

Function/effects

The excavation of tunnels and holes will result in stress redistribution in the rock around the repository and thereby creating a disturbed zone. Rock blasting creates new fractures in the innermost part of this zone closest to the tunnels. The main effects on the radionuclide transport are a disturbed groundwater flow system and disturbed pathways around the repository. The altered transport resistance between the bentonite buffer and adjacent rock will also influence the long-term stability of the bentonite buffer. The heat generated from the spent fuel will affect the geochemistry, the groundwater flow and the mechanical stability of the rock.

Characteristics

The characteristics determining the effects of the disturbed zone and the transport in the near-field are listed below:

- gradients (hydraulic, thermal and gas)
- extension of disturbed zone
- permeability of disturbed zone
- hydraulic contact between disturbed zone and fracture zones
- hydraulic contact between disturbed zone and bentonite buffer
- diffusivity
- sorption properties
- geochemical environment
- mechanical properties of disturbed zone
- thermal properties of disturbed zone
- redox front behavior.

Technical factors

The technical factors which will have an influence on the radionuclide transport in the near-field rock and the evaluation of a disturbed zone are listed below:

- excavation methods
- temperature distribution
- avoidance of highly conductive fractures
- sealing of highly conductive fractures, methods and effects
- avoidance of fracture zones
- sealing of fracture zones, methods and effects
- repository depth.

Potential differences in the release from the near-field

There are a number of possible transport pathways for nuclides escaping from a penetrated canister, see Section 4.3.4. Some paths are not applicable for all repository concepts. The disturbed zone around the tunnels/deposition holes are thought to be the dominating transport pathway for radionuclides to fracture zones intersecting the deposition area. Two processes have been studied in this comparison:

- Transport to and in the disturbed zone around the tunnels.
- Transport to a subhorizontal fracture zone.

The paths and properties that have been considered for the transport in the near-field are for the four concepts:

KBS-3

- Diffusion through the bentonite to the disturbed zone surrounding the deposition hole and subsequent transport in the disturbed zone surrounding the deposition hole, or through a fracture intersecting the deposition hole, to the disturbed zone around the tunnel.

- Diffusion upwards in the bentonite in the deposition hole to the disturbed zone around the drift.

- Diffusion upwards in the bentonite in the deposition hole to the backfill in the drift, and subsequent transport into the disturbed zone around the drift or directly into fractures/ fracture zones intersecting the drift.

- Diffusion through the bentonite and transport through the rock to a fracture zone located close to a deposition hole.

- Water flow in the disturbed zone around the drift.

VLH

- Diffusion through the bentonite into the disturbed zone around the deposition tunnel or directly into fracture openings in the deposition tunnel.

- Diffusion through the bentonite into the disturbed zone around the deposition tunnel and transport from the disturbed zone through the rock to a fracture zone located close to the deposition tunnel.

- Water flow in the disturbed zone.

MLH

- Diffusion through the bentonite into the disturbed zone around the tunnel or directly into fracture openings in the deposition tunnel and transport away from the deposition tunnel in this fracture.

- Transport in the disturbed zone around the deposition tunnel to the disturbed zone around the access tunnel.

- Transport from the disturbed zone through the rock to a subhorizontal fracture zone located close to the deposition tunnel.

- Water flow in the disturbed zone.

VDH

- Diffusion through the bentonite to a fracture opening in the deposition hole and into the disturbed zone around the deposition hole.

- Advection within the bentonite mud in the deposition hole to an intersecting fracture/ fracture zone.

- Water flow in the disturbed zone.

Migration pathways

Since the transport in the disturbed zone around the tunnel is deemed to be very similar for the KBS-3, VLH and MLH alternatives, the paths for reaching the disturbed zone should be compared. In the VLH and MLH concepts only one path from canister to the disturbed zone is active, the diffusion through the 0.4 m thick bentonite buffer. The KBS-3 alternative has two major pathways, diffusion through the bentonite to the disturbed zone around the deposition hole and then migration in a fracture intersecting the deposition hole or within the disturbed zone around the deposition hole to the disturbed zone around the tunnels. The bentonite surrounding the canisters are about the same in the alternatives, but the transport distance through the fracture to the disturbed zone around the tunnel or a distance within the disturbed zone around the deposition hole is an additional barrier in the KBS-3 alternative. The other transport path from the KBS-3 canister is the diffusion upwards through the bentonite in the deposition hole. The distance from the canister lid to the tunnel is several times larger than the bentonite thickness for radial diffusion. Therefore both transport paths for the KBS-3 concept are longer and more favorable, than for the VLH and MLH concepts.

A transport path that is independent of the disturbed zone around the tunnel can be envisioned for the KBS-3 concept if a subhorizontal fracture zone is located near the bottom of the deposition hole. Radionuclides transported through the bentonite are released into a fracture intersecting the deposition hole and subsequently transported through this fracture to the subhorizontal fracture zone. This path is less probable for the VLH and MLH concepts since the disturbed zone circumvents the canisters and will act as a cage for escaping radionuclides.

The water flow rate in the disturbed zone around the deposition tunnels in a MLH and VLH repository will be lower than in the disturbed zone around the drifts above the deposition holes for KBS-3 because of the smaller extension of the disturbed zone. On the other hand, if the comparison is made between the deposition tunnels and the deposition holes for KBS-3, the disturbed zone around the horizontal deposition tunnels will probably be subject to larger water flow rates than the disturbed zone in the vertical deposition holes. The deposition tunnels for the MLH alternative are connected to the blasted access tunnels at both ends and can serve as a conductor between the larger tunnels, whereas the vertical deposition holes are "dead-end" constructions. On the other hand is a "dead-end" construction also technically possible for the MLH alternative.

Retardation in disturbed zone

Once emerged into the disturbed zone the radionuclides will be retarded compared to the water velocity. An important parameter for this retardation is the area available for surface sorption and sorption on the inner surfaces of the rock matrix. Even non-sorbing nuclides will be retarded because they can diffuse in the porous rock matrix and thus access a large volume of stagnant water. The added residence time while the nuclide resides in the matrix water may be several orders of magnitude larger than the residence time of water flowing in the fractures in the disturbed zone. Since the hydraulic conductivity as well as the pressure gradient are assumed to be the same for the KBS-3, VLH and MLH concepts, no difference in water flowrate is expected. The retardation of the radionuclides, especially sorbing species, is dependent on the available flow wetted surface per volume of flowing water. The flow wetted surface area is not expected to be significantly different between the concepts, why no difference regarding the transport of radionuclides around the tunnels can be identified.

Impact of generated heat

The results in Appendix 2 show that the water flow rates in the disturbed zone around the KBS-3 and VLH tunnels will likely be limited by the hydraulic conductivity in the disturbed zone itself and not by the water inflow from intersecting 2nd and 3rd order fracture zones. This is probably also the case for the MLH and VDH concepts. The hydraulic conductivity in the disturbed zone in the VDH concept is the same as in the

KBS-3 concept and the extension of the disturbed zone is smaller than in the other concepts. There is, however, a severe lack of data relevant for large depths.

Even if the hydraulic conductivities in the disturbed zones are similar in the concepts, implying the same water flowrates, the heat generated from the canisters might affect the radionuclide transport differently. The heat will during an initial "short" time period of some hundred(s) of years induce a thermal gradient that might enhance the radionuclide transport. The KBS-3, VLH and MLH canisters will have a lifetime considerably longer than the duration of the thermal gradient and the disturbed zone around the tunnels will for these concepts be directed perpendicular to the water movement caused by the generated heat. On the other hand, the canisters in the VDH concept may initially be damaged and the main conductivity in the disturbed zone around the deposition holes will have the same direction as the water movement caused by the heat. This upward movement of water and radionuclides in the VDH concept will be counteracted by the density gradient caused by the high salinity groundwater at great depths. Determination of the net effect of these two counteracting effects has not been addressed in this study.

Bentonite plugs will separate the canisters in the VDH concept, but the relatively high hydraulic conductivity in the bentonite mud surrounding a canister and the heat generated from the fuel might induce advective transport of nuclides within the deposition hole between the bentonite plugs. This advective transport within the bentonite mud might enhance the release rate if a fracture or fracture zone intersects the deposition hole over this distance. This effect is not considered to be of importance for the KBS-3 or VLH concepts because of longer canister lifetimes and lower hydraulic conductivities in the bentonite surrounding the canisters.

Conclusions

The disturbed zone is considered to be of large importance for the radionuclide transport once nuclides have escaped the bentonite. Radionuclides escaping from a canister in a KBS-3 repository will have a larger number of possible paths to the disturbed zone around the drift compared with the VLH and MLH concepts. However, the paths will be longer and give a larger transport resistance for the KBS-3 concept.

The transport to subhorizontal fracture zones is of importance since these zones often have high hydraulic conductivity and therefore might act as fast pathways to the biosphere. Radionuclides escaping from a KBS-3 repository might end up in a subhorizontal fracture zone while this alternative is less probable in the VLH concept because of the presence of the disturbed zone around the deposition tunnels.

The heat generated by the fuel in the canisters will not be of any importance in the KBS-3, MLH and VLH concepts because of the "short" time for heat generation and the direction of the disturbed zones. In the VDH concept, the radionuclides will be mobile during the time for heat generation due to initially failed canisters and the disturbed zone will have the same direction as the water movement due to the generated heat.

5.2.4 Far-field

The far-field barrier is defined as the undisturbed rock trough which radionuclides have to migrate before reaching the biosphere.

Function/effects

The hydrological conditions in the rock have a direct influence on the transport of radionuclides with flowing groundwater. Low groundwater flowrates in the rock at repository level together with a large surface area available for sorption and matrix diffusion is positive in order to delay the radionuclide release to the biosphere and thereby give time for radionuclide decay. The maximum release rate to the biosphere of radionuclides with short period of release will be reduced. Other positive effects are that the rock provides a suitable and stable geochemical environment, providing mechanical protection against external events and also protecting the repository from intrusion.

Characteristics

The characteristics determining the radionuclide transport in the far-field are listed below:

- gradients (hydraulic, density, thermal)
- fracture zones (geometry, conductivity)
- rock mass (permeability)
- water flow paths (frequency, geometry, flow wetted surface)
- radionuclide travel distance
- geochemical environment
- sorption properties
- matrix diffusivity
- rock mechanical properties
- rock stress field
- thermal properties.

Technical factors

Technical factors which will have an influence on the prediction of rock characteristics and on the evaluation of the radionuclide transport in the far-field are listed below:

- repository depth
- repository dimensions
- design and construction of shafts, ramps and access tunnels
- sealing of shafts, ramps and access tunnels
- possibility for prediction of characteristics from site evaluation
- possibility for prediction of characteristics from excavation
- possibility to ensure safety distance to major fracture zones.

Potential differences in the release from the far-field

The far-field rock is the last barrier prior to the biosphere if the canister has failed and the radionuclides have been transported through the near-field. The processes and properties that have been considered in the comparison for the transport of radionuclides in the far-field are compiled as follows:

- transport mechanisms
- distance to subhorizontal fracture zones
- number of and distance to intersecting fracture zones
- transport length and paths
- gradients.

Transport mechanisms

No differences have been identified between the KBS-3, MLH and VLH concepts in the transport mechanisms for radionuclides in the far-field rock. Very little is known about transport of radionuclides at great depths, but there is reason to believe that sorption onto rock surfaces, diffusion into the rock matrix and sorption within the rock matrix are mechanisms that are valid also at great depths. A mechanism that might change with depth is the flow within fracture planes. Several investigations have concluded that water flows in preferential paths, channels [*Abelin, 1986, Abelin et al., 1987, Abelin et al., 1990, Birgersson et al., 1992*]. These investigations have mainly been performed in boreholes/tunnels at most some hundreds of meters below the surface. The increased rock stresses at very great depths might induce even more pronounced channeling effects within the fracture planes and thereby reduce the surface area available for sorption and diffusion into the rock matrix. This could give rise to transport pathways with less retardation at larger depths for radionuclides escaping from a VDH repository, but the deeper location will still be an advantage for the VDH concept.

Distance to subhorizontal fracture zones

Subhorizontal fracture zones are often highly conductive and may be important features for connecting a repository with other fracture zones emerging in the biosphere. The extensions of a KBS-3 and MLH repository will be less than 1*1 km and the extension of a VLH repository will be 4.5 km. The longer extension of a VLH repository implies that it will be more difficult to avoid being close to subhorizontal fracture zones. On the other hand, as pointed out in Section 4.3.4, radionuclides escaping from a VLH repository are less likely to emerge into a subhorizontal fracture zone because the disturbed zone around the deposition tunnel will act as a cage for escaping radionuclides. The uncertainties in the existence of subhorizontal fracture zones near the repositories result in the conclusion that no significant difference is expected between the KBS-3, VLH and MLH concepts.

The deposition holes in the VDH concept will probably be intersected by one or several subhorizontal zones. The respect distance to these zones will be very small, if any, because of practical difficulties to characterize the location of fracture zones in boreholes as deep as 4000 m.

Number of and distance to intersecting fracture zones

A VLH repository will be intersected by a larger number of fracture zones and will also have a shorter respect distance to the fracture zones compared with a KBS-3/MLH repository, see Appendix 1.

A MLH repository has a similar extension as a KBS-3 repository and will therefore intersect about the same number of fracture zones.

A VDH repository will be intersected by fewer fracture zones than the repositories proposed to be located at 500 m depth due to a lower fracture frequency at larger depths. The respect distance to the fracture zones might, however, have to be assumed to be very small because of difficulties to characterize fracture zone locations as deep as 4000 m.

Transport length and paths

The canisters are proposed to be located at the 500 m level both in the KBS-3, MLH and VLH concepts. This will give the same transport lengths in the far-field rock for escaping radionuclides. The migration distance for escaping radionuclides within the disturbed rock around the tunnel will, however, be somewhat shorter in the VLH concept because of a larger number of intersecting fracture zones.

The different layouts of these two concepts will influence the impact of defect canisters. A large flow path connected to the biosphere and close to the repository might transport radionuclides from many of the defect canisters in a KBS-3 or MLH repository due to the limited extension of that repository. A large flow path close to a VLH repository would probably affect a smaller number of defect canisters because of the long extension of the VLH tunnels. Furthermore, the long extension of a VLH repository will give a larger number of intersections with fractures and fracture zones which implies that escaping radionuclides would probably be found in a larger number of locations in the biosphere compared to radionuclides escaping from a KBS-3 repository if several canisters are penetrated. The concentrations of radionuclides in the water discharged into the biosphere could thereby be lower, but a larger area will be contaminated.

Radionuclides escaping from a VDH repository will have to migrate at least 2000–4000 m in the far-field rock before emerging into the biosphere. Compared to KBS-3, MLH and VLH, radionuclides escaping from a VDH repository will spend a longer time in the far-field rock allowing a larger portion of the nuclides to decay. The long transport path will also decrease the peak concentration of the nuclides as the transport proceeds because of interaction with fracture surfaces and the rock matrix. The nuclides will probably emerge at a large number of locations in the biosphere but in low concentrations. It is not clear to what extent the severe channeling, that has been observed in field experiments [*Abelin, 1986, Abelin et al., 1987, Abelin et al., 1990, Birgersson et al., 1992*], can reduce the barrier effect of the additional far-field travel distance.

When a KBS-3, MLH or VLH repository has been backfilled there will be a ramp/shafts connecting the repository with the surface. These will be plugged with bentonite or a sand/bentonite mixture. The canisters in the VDH concept will be placed in a number of boreholes drilled from the surface that will be sealed off with bentonite, concrete and asphalt, see Section 3.5.3. All these shafts, ramps and boreholes extending to the repository level will be plugged with bentonite or sand/bentonite mixtures giving hydraulic conductivities lower than the surrounding rock, but the disturbed zones around these shafts/ramps/boreholes will have high hydraulic conductivities and could therefore constitute potential pathways for escaping radionuclides. To find a reliable method to prevent this axial flow along a few shafts/ramps, as in the KBS-3, MLH and VLH concepts, is probably easier than to do a similar operation in a large number of very deep boreholes. The disturbed zones around the deposition holes in the VDH concept might then act as transport pathways for escaping nuclides to more shallow water and/or to the biosphere.

Salt gradient

Waters at very large depths in the bedrock are known to have high salinity implying a vertical density gradient that would counteract any upward movement of water. This would then prevent, or at least significantly reduce, water at large depths to be mixed with more shallow water and thereby preventing/reducing radionuclides to emerge from large depths into the biosphere. This effect is supposed to be of importance for a repository located as deep as VDH, but not for KBS-3, MLH or VLH. There will, however, be a problem to demonstrate that this preventing/retarding effect exists and will continue to exist for long time periods in the future.

Temperature gradient

The temperature as function of time at the repository level will be somewhat different for the different concepts. The canisters will in the KBS-3 and MLH concepts be placed within a smaller area compared with the VLH and VDH concepts giving a longer time for the temperature decrease. The maximum temperature in the rock around a VLH repository will be obtained after about 10 years compared to about 100 years for a KBS-3 repository [*Pusch and Börgesson, 1992*]. Differences in the surrounding rock temperature will be maintained for a time period of a few, maybe up to ten thousands of years. This will induce a difference between the VLH and KBS-3, MLH concepts in the transport for radionuclides escaping during this time period in such a way that the transport from a KBS-3 or MLH repository might be enhanced because of the higher temperature. The duration of the induced temperature gradient is, however, short giving that the identified difference in the heat cycle is considered to be of minor importance.

Hydraulic gradient

No differences have been identified between the VLH, MLH and KBS-3 concepts that should result in different hydraulic gradients. The hydraulic gradient in the rock at 2000–4000 m level will probably be lower than at the 500 m level. This implies a lower water flowrate at large depths giving the nuclides a longer time for decay and interaction with fracture surfaces and the rock matrix for the VDH concept.

Conclusion

A VLH repository will be intersected by a larger number of fracture zones and will also have a shorter respect distance to the fracture zones compared with a KBS-3 or MLH repository. Radionuclides from a VLH repository with many defect canisters would therefore be found at a larger number of locations in the biosphere but in lower concentrations compared to a KBS-3 repository.

A VDH repository would be intersected by fewer fracture zones due to a lower fracture frequency at large depths [*Juhlin and Sandstedt, 1989*]. The respect distance from some of the canisters to the intersecting fracture zones will, however, probably be very short due to practical problems to characterize boreholes as deep as 4000 m. The radionuclides would therefore have easy access to intersecting fracture zones and thereby into the far-field rock. The increased salinity at great depths gives a density gradient that could prevent radionuclides escaping from a VDH repository to emerge into the biosphere. This effect is, however, difficult to demonstrate and it will be even more difficult to assure that this effect will exist for long time periods.

5.2.5 Biosphere

The biosphere is here regarded as the receptor of radionuclides discharged from the far-field, i.e. soils, sediments and water bodies.

Function/effects

In the biosphere dilution of radionuclides in physical components of the biosphere (surface groundwater, lakes, sea) and also accumulation in physical components of the biosphere (soils, sediments) will take place.

Characteristics

Characteristics determining dilution and accumulation of radionuclides in the biosphere are:

- volumes and turn over rate of the receptors
- behaviour of radionuclides in the receptors.

Technical factors

Factors influencing the biosphere performance are listed below:

- influenced by site selection, e.g. below the Baltic Sea
- biosphere evolution with time.

Potential differences in the radionuclide transport in biosphere

The primary receptors in the biosphere to which radionuclides are released from the geosphere are site-dependent, and these primary receptors as well as subsequent potential pathways for nuclides to reach man will change as a consequence of the evolution of the biosphere. Even if the same site is considered in all concepts, the primary receptors could be different because of differences in the stage of evolution of the biosphere at the time of release. The uncertainties associated with the biosphere evolution and to some extent also the lack of a quantitative estimate of the time of nuclide release from the geosphere makes it difficult to identify potential differences between the concepts in this respect. However, one difference of potential importance, which is connected to the extension of the repository, has been identified and is discussed below.

Radionuclides are transported through the geosphere mainly in fracture zones in the rock. The larger the number of fracture zones carrying the nuclides the larger the number of potential primary recipients in the biosphere and the smaller the amount of nuclides reaching each biosphere recipient. The maximum individual dose arising from each primary recipient in the biosphere should then decrease as a function of the number of primary receptors in the biosphere, but the collective dose might be the same. It is of course possible that two or more fracture zones will discharge their water into the same primary recipient in the biosphere. In this case the recipient has to be quite large, for example a lake or the sea, which also means a large dilution which reduces the nuclide concentration in the recipient and the potential maximum individual dose.

From the discussion above and in Chapter 4 it could be concluded that a VLH and a VDH repository could be more favorable than a KBS-3 or MLH repository for a large number of failured canisters because of the larger number of fracture zones intersecting the repository area.

5.3 Comparison of repository systems

The long-term safety of a repository will depend on the performance of the total system rather than the performance of a single barrier. In a comparison between different repository alternatives, the evaluation of the safety of the individual barriers must therefore be combined with an evaluation of to what degree the overall safety depends on the function of an individual barrier.

To evaluate the performance of the repository systems the comparison criteria defined in Section 5.1.3 have been used:

- Dose limit criteria
- Multiple barrier principle
- Possibility of validation
- Sensitivity to rare events.

5.3.1 Dose limit criteria

To evaluate if the dose limit criteria is fulfilled for a repository concept a safety analysis of the concept must be performed. In the safety analysis the long-term performance of the repository and the radionuclide release to the environment are quantitatively estimated by predictive modelling.

In this study no calculations of radionuclide releases with resulting doses have been performed. Therefore only potential differences or similarities in aspects of importance for the evaluation of environmental consequences are discussed.

The dose estimated from a certain radionuclide release from the geosphere should only be seen as an indication of potential consequences for the environment since this dose is based on current living habits. The problems involved in predicting the future evolution of the biosphere and the habits of human livings will be the same for all the studied concepts.

Uncertainties in estimated doses

The estimation of doses for different scenarios will always include uncertainties. The uncertainty can be conceptual and originate from limited observability and knowledge of the system structure as well as arise because of limited identification or understanding of the processes determining the release. Uncertainties will also be introduced in the modelling by the transformation of systems or processes into mathematical models. The models require data and these data include uncertainties from measurements, lack of completeness and representativeness.

The canister lifetime will strongly influence the release of some radionuclides, especially relatively short-lived. The prediction of canister lifetimes for KBS-3, MLH and VLH will include the same degree of uncertainties as the canisters are manufactured from the same materials and the environmental conditions are the same. In the VDH concept both the canister material, the emplacement technique and the environmental conditions differ and the uncertainties in predictions of canister lifetime cannot be directly compared but is assessed to be larger than in the other concepts.

Uncertainties in the estimates of the release from the near-field, including the release from canister and transport in bentonite buffer and disturbed zone, are for KBS-3, MLH and VLH assessed to be similar. The evaluation of the concepts will include the same conceptual, modelling and data uncertainties due to the similarity between the concepts. The uncertainties in the estimates of the near-field release in the VDH concept are assessed to be larger for the same reasons as given above and, in addition, due to limited observability and understanding of processes of potential importance for the radionuclide release.

Since both KBS-3, MLH and VLH is located at a depth of 500 m, the uncertainties associated with the transport and release from the far-field are similar. The major uncertainties in the far-field release arise from the uncertainties in the conceptual understanding of the geosphere transport and in the representativeness of data. For the VDH concept which is located at a much larger depth additional uncertainties what concern the role of the salt gradient will be introduced.

Uncertainties in the prediction of future environmental conditions will influence the estimated doses to the same degree for all concepts.

5.3.2 Multiple barrier principle

The performance of the repository barrier system will to different degree be dependent of the performance of the processes in the barriers. The repository barrier system consists of the various processes and mechanisms for isolation or radionuclide retention in the canister, the near-field including the bentonite buffer and the disturbed zone, the far-field and the biosphere.

The importance of individual barrier performance for the estimated dose from the repository is to some extent nuclide specific. Here, the importance is only qualitatively addressed for different types of radionuclides.

KBS-3

As long as the canister is intact or offers a large transport resistance, the function of the other barriers are of minor importance. For relatively short-lived radionuclides with high mobility the canister is of major importance. For long-lived radionuclides with high mobility a distribution in canister failure time is of importance.

The transport resistance in the bentonite buffer is of substantial importance for short-lived radionuclides at early canister failure but of limited importance for long-lived radionuclides.

The extension and properties of the disturbed zone around the deposition hole and the storage tunnels can play a major role both for the nuclide release from the buffer or the backfill and for the release to the far-field. The disturbed zones can offer shortcuts to fracture zones in the far-field.

The main effect of the far-field is to delay the arrival of the radionuclides in the biosphere. If the delay is long enough radionuclides will decay during the transport and the release of nuclides to the biosphere is strongly decreased. For sorbing radionuclides the delay in the geosphere can be substantial.

The potential dilution and accumulation of radionuclides in the biosphere are essential for the estimates of the radiologic consequences, but the evolution of the biosphere in the long-term perspective must be regarded as uncertain.

In summary it could be stated that all barriers in a KBS-3 repository will contribute to reduce the radionuclide release to the environment, and that the long-term performance most likely not is dependent on an individual process or mechanism in the barriers..

VLH

In a comparison of the multiple barrier function of VLH with the KBS-3 concept it is obvious that the concepts are very similar. The extent to which the different components act as barriers may differ, but likewise to KBS-3, the long-term performance of VLH will most probably not depend on the performance on an individual process or mechanism.

MLH

The comparison of the multiple barrier function of MLH with KBS-3 lead to the same conclusion as for VLH above.

VDH

In VDH, uncertainties regarding integrity and behaviour of canister and bentonite buffer after deposition makes it difficult to place credit in them as good barriers for radionuclides. Therefore, without access to more detailed analyses including radionuclide release calculat-ions for the VDH near-field, it is assessed that the long-term performance and safety to a large extent rely on only retardation potential of the far-field rock. However, this barrier might be very effective because of long transport paths, which in the most advantageous case never reach the biosphere.

5.3.3 Possibility of validation

The validation of the long-term performance of the barriers and the repository system will always be associated with large uncertainties. For technical barriers these uncertainties are mostly due to the extrapolation in time of often rather well known short-term behaviour, while both extrapolation and presently limited understanding of the short-term behaviour of the far-field rock makes validation of the performance of this barrier complicated.

In comparing the concepts regarding possibility of validation no difference is expected between KBS-3, VLH and MLH. In all 500 m level concepts, the long-term performance will to a large extent be dependent on similar technical barriers and the natural barriers are also similar.

In VDH, the difficulty in predicting the conditions immediately after deposition makes even the short-term behaviour of the technical barriers difficult to estimate and consequently also difficult to validate. In addition, the possibility of validating and demonstrating the potentially large barrier capacity which is associated with the transport from the deposition zone at great depths to the biosphere is assessed to be low with the present limited understanding of how water flows deep down in the rock.

5.3.4 Sensitivity to rare events

In the evaluation of repository performance the sensitivity to rare events is also addressed by making quantitative estimates of the consequences in terms of radionuclide release and dose to man. Here, the sensitivity to major faulting and human intrusion is only qualitatively compared.

Glaciation leading to major faulting

The most severe consequence of faulting in conjunction with glacial advances and retreats would in KBS-3, VLH and MLH be a damaged canister. The movements that occur due to the pressure from the ice is thought to be at existing major fault zones. The location of the repository will be such as to avoid these major zones. There is a very slight risk that new fault zones is formed as a consequence of glaciation, and in this scenario the VLH concept would be more sensitive due to the geometry of the repository. However, the probability of this event is considered to be very low so this difference is not of major importance. Smaller movements in the near-field rock (5–10 cm) can induce deformations to the KBS-3/MLH and VLH canisters but will not cause a rupture of either canister type. A movement of this magnitude is more likely to cause major damage to a VDH-canister due to the short distance between canister and near-field rock and the weaker canister construction.

Intrusion

The likeliness of an accidental intrusion into the repository, by drilling a drinking water well in the vicinity of the repository, is mainly dependent of the depth of the repository. There is no difference between the 500 m level repositories in this aspect but the VDH has a significant advantage. A willful intrusion into a VDH repository is also more unlikely because of the lower value of the canister material and is probably much more dangerous to perform because of the high probability that canisters have been damaged during the deposition. The larger extension of a VLH repository can increase the risk for accidental intrusion compared to a KBS-3 or MLH repository.

6. RANKING

6.1 General

In order to rank the alternatives a comparison must be performed of well defined activities/areas of potential importance for the performance and long-term safety of the repository systems.

6.2 Selected methodology

The attempt to rank of the repository concepts is based on differences in the performance of individual barriers within the concept as well as on the performance of the integrated repository barrier system. To evaluate and compare the performance of the repository systems a set of comparison criteria has been used. The comparison considers uncertainties involved in the estimates of doses, the importance of individual barriers for the overall performance, possibilities to validate and demonstrate the long-term performance and the sensitivity to rare events, see Section 5.1.

6.3 Summary of comparison of repository concepts

The ranking of the repository systems is based on the performance of individual barriers and the total repository systems presented in Sections 5.2 and 5.3 for KBS-3, MLH, VLH and VDH.

The comparison of the repository systems is performed by comparing the VLH, VDH and MLH concepts with the KBS-3 concept

VDH

The long-term safety of a VDH repository is potentially as good as the long-term safety of a KBS-3 repository, but the possibility to demonstrate the long-term safety of the VDH concept is assessed to be lower than for the KBS-3 concept. This statement is mainly based on the following facts:

- In the VDH concept quality control of emplaced canister and surrounding buffer material is difficult to achieve. The importance of these barriers for the safety of the repository will therefor be very uncertain and it assumed that the integrity of these barrier is lost already after deposition.

- The performance of the repository concept must rely mainly on the function of the processes in the far-field rock. The far-field rock is potentially a very good barrier for escaping radionuclides, but the uncertainties involved in predictions of the far-field migration are assessed to be large.

VLH

The long-term safety and the possibility to demonstrate the long-term safety of the VLH concept involves similar difficulties and uncertainties as the KBS-3 concept. A ranking of the two concepts is difficult. However, advantages and disadvantages with VLH compared to KBS-3 of potential importance for the performance of the repository are listed below.

Advantages:

- The shorter duration of elevated temperature in the near-field rock in VLH means a shorter time with potentially higher groundwater flow along the bentonite buffer. This difference is, however, assessed to be of minor importance since the period of elevated temperature occurs prior to canister failure in both concepts and because the effects on bentonite alteration is expected to be small in both concepts.

- The disturbed zone around the drift in VLH will potentially act as a hydraulic cage preventing nuclide transport to undetected subhorizontal fracture zones close to the deposition tunnel which may constitute major transport paths to the biosphere.

- The simpler design of VLH repository without holes drilled perpendicular to the drift will probably mean a smaller risk of movements in the near-field rock.

- The long horizontal extension of each deposition drift in VLH means that a larger number of water conducting discontinuities intersects the drift. This in turn implies that the possibility is higher that escaping radionuclides are distributed between several primary receptors in the biosphere if more than one canister is leaking.

Disadvantages:

- The larger canister in VLH is more sensitive to external load once corrosion of the inner supporting steel canister is initiated. Therefore, the risk seems to be higher that a larger hole or break in the canister is created. In addition, the life-time for the steel canister in an initially defect copper canister may be shorter.

- The vertical position of the canister means a higher probability of a disadvantageous location of the hole or break what concerns potential effects of gas on radionuclide release from the canister.

- The larger amount of fuel stored in each canister also means that the total amount of radionuclides released per failed canister is larger.

- The transport paths from the canister to the disturbed zone around the drift where the main flow is expected to occur is shorter. In addition, the available sorption capacity is smaller considering that radionuclides escaping from a canister in KBS-3, for several transport paths, may pass more bentonite or rock before reaching the disturbed zone around the drift .

- The larger number of fracture zones intersecting a VLH repository and the shorter respect distance to the fracture zones means that nuclides will have a higher potential for getting access to a major flow path through the geosphere, irrespective of the location of the leaking canister(s).

- The longer vertical extension in one direction of a VLH repository and the larger number of fracture zones that intersects the drifts makes a VLH repository more sensitive to the formation of fault zones and to movements in existing fracture zones. However, this difference is assessed to be of minor importance since the risk of new faults to be formed is small, and movements will mainly occur in major existing fault zones which should be possible to avoid when constructing the repository.

MLH

The long-term safety and the possibilities to demonstrate the long-term safety of the MLH concept involves the same difficulties and uncertainties as the KBS-3 and no ranking between the concepts is made. Here only advantages and disadvantages of potential importance in comparison with the KBS-3 are presented.

Advantages:

- The disturbed zone around the drift in MLH may act as a hydraulic cage preventing nuclide transport to subhorizontal fracture zones which may constitute a transport paths to the biosphere.

- The simpler design without vertical holes drilled perpendicular to the drift will probably mean a smaller risk of movements in the near-field rock and thus limit the number of near-field transport paths created during the construction.

- The access tunnels and specifically the roof of these tunnels may attract a very large portion of the water flow through the repository and thereby limit the amount of water flowing around the deposition tunnels, on the other hand the disturbed zone around the deposition tunnel will be connected to the disturbed zone around the access tunnels. Model calculations could indicate if this effect is likely to be an advantage or disadvantage of any significance.

- If the flow of water around the deposition tunnel is smaller than around the access tunnels and around the tunnel above the deposition holes for KBS-3, the transport along the deposition tunnel will be an additional barrier.

Disadvantages:

- The horizontal positioning of the canister means a higher probability of a disadvantageous location of the hole or break concerning effects of gas formation on radionuclide release from the canister.

- The transport paths from the canister to the disturbed zone around the deposition tunnel is shorter. On the other hand the distance to reach the access tunnel is much longer for most of the canisters.

6.4 Concluding remarks

The ranking of the repository concepts was carried out by comparing the VDH, VLH and MLH concept with the KBS-3 concept. The performance and long-term safety of the repositories located at 500 m level will be based on a multiple barrier system and the predictions for the concepts will involve similar uncertainties. The differences that have been identified in the performance of the various mechanisms for isolation and retention are not distinguishing any of the concepts as more favourable than the others with respect to overall safety. The conclusion is also that all the 500 m level alternatives can be expected to comply with strict requirements concerning the long-term safety. The performance and long-term safety of the VDH concept is determined by the function of only one individual barrier and does not fulfill the multiple barrier principle in the same way as the other concepts.

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Appendix 1

Discontinuities intersecting KBS-3/MLH and VLH repositories

A KBS-3/MLH repository is proposed to be located in a 1*1 km plane. The canisters in the VLH concept will be disposed in three parallel drifts, each about 4.5 km in length. This appendix examines the influence of these different repository geometries on the number of different order discontinuities each repository is likely to intersect. Table A 1-1 gives a compilation of the rock characteristics that are expected to be found at the 500 m level. The background material is found in Appendix 6. Table A1-2 gives a comparison of the number of different order discontinuities that are supposed to intersect the two considered repository layouts and the respect distance to the discontinuities. The number of intersections with discontinuities have been discussed in Sections 3.2.5 and 3.3.5. The given respect distances are suggestions applied in PASS in order to get numbers for primary use in the cost comparison study. The numbers given on intersections with discontinuities are very rough estimates that will be highly dependent on the discontinuity pattern at the site where the repository is to be located. However, significant differences in the numbers between the concepts should reflect differences one should expect to find at any potential site if the assumed rock characteristics give a fair description of the site.

Table A1-1 Rock characteristics at the 500 m level to be used in this study.

Discontinuity	Spacing perpendicular/parallel [m]	Width [m]	Hydraulic conductivity [m/s]
1st order	3200/6900	50-150	10^{-7}
2nd order	400/800	1-20	10^{-8}
3rd order	50-100	0.5-2	10^{-9}
4th order	0.4/0.8	0.01	10^{-11}
Subhorizontal fracture zone	700	?	10^{-7}

Table A1-2 Comparison of respect distance and number of discontinuities intersecting KBS-3/MLH and VLH repositories.

	KBS-3/MLH Number of intersections	Respect distance [m]	VLH Number of intersections	Respect distance [m]
1st order	0	>1000	0	<1000
2nd order	24	<100	3*(5-10)	20-40
3rd order	20-40	<10	3*(50-100)	2-5
4th order	Many	0	Many	0
Subhorizontal fracture zones	0	100?	0?	<100

The overall conclusion from the data given in Table Al-2 is that a repository with a linear extension (VLH) will be intersected by a larger number of discontinuities and will have a shorter respect distance to the discontinuities than a repository proposed to be located in a square plane (KBS-3/MLH). From a practical point of view it would probably be easier to characterize the discontinuities within a 1 * 1 km square than a 4.5 km line. This would then decrease the risk for unpleasant surprises during the construction phase of the repository.

The different layouts of the concepts will influence the impact of defect canisters. A major flow path connected to the biosphere and close to the repository might transport radionuclides from many of the defect canisters from a KBS-3/MLH repository due to the limited extension of that repository. One (or a few) large flowpaths intersecting a VLH repository would probably not affect all defect canisters because of the long extension of the VLH tunnels. This is a advantage for a VLH type repository, since the effect of a not detected fracture zone or a zone formed sometime in the future would be limited to a smaller number of canisters. Because of the long extension, radionuclides from a VLH repository would probably be found in a larger number of locations in the biosphere then radionuclides from a KBS-3/MLH repository if a large number of canisters are defect. This can however be an advantage or a disadvantage. The concentrations of radionuclides in the biosphere will probably be lower since the nuclides will emerge at a larger number of locations, but a larger area of the biosphere will be contaminated.

Appendix 2

Water flow in the near-field rock and the formation of illite

This appendix examines the possibility of bentonite conversion into illite due to presence of potassium ions (K^+) in the groundwater. Illite has a higher hydraulic conductivity and considerably lower swelling ability compared to bentonite, why illite formation would have a negative effect on the clay barrier. The transport rate of K^+ from the groundwater to the intact bentonite will be controlled by either the diffusion rate or the amount of groundwater containing K^+ that is in contact with the clay.

Diffusion controlled formation - shrinking core model

A shrinking core model has been used to estimate the time needed for conversion of the bentonite into illite.

Assumed data:

Concentration of K^+ in groundwater	$C= 13$ mg/l$=13*10^{-3}$ kg/m^3
Effective diffusivity of K^+ in bentonite/illite	$D=10^{-10}$ m^2/s (conservative)
Density of bentonite	$\rho=2*10^3$ kg/m^3
Transformation constant	0.1 kg K^+/kg montmorillonite
Bentonite composition	0.7 kg montmorillonite/kg bentonite

The bentonite density, the transformation constant and the composition of bentonite gives that 140 kg K^+ is needed to transform one m^3 of bentonite into illite. This constant is denoted as L.

The shrinking core model for planar geometry gives:

$$x_s = \sqrt{\frac{2D_e tC}{L}}$$

where x_s is the penetration depth of K^+ into the clay barrier, which in this case equals the distance converted to illite.

The canisters will for both the KBS-3 and VLH concepts be surrounded by bentonite with a thickness of about 0.4 m. Inserting x_s = 0.4 m in the above equation gives the time for complete conversion of the bentonite surrounding a deposition hole into illite.

$$t = \frac{x_s^2 L}{2D_e C} = \frac{0.4^2 * 140}{2 * 10^{-10} * 13 * 10^{-3}} = 2.7*10^5 \ years$$

The above calculation assumes that the amount of groundwater containing K^+ is unlimited and that the transport is only determined by diffusion. The amount of K^+ needed per m^2 depends on the volume to surface area ratio for the backfill.

$$KBS\text{-}3 : V/A = \frac{\pi * (0.8^2 - 0.4^2) * length}{\pi * 2 * 0.8 * length} = 0.3 \ m^3/m^2$$

$$VLH : V/A = \frac{\pi * (1.2^2 - 0.8^2) * length}{\pi * 2 * 1.2 * length} = 0.33 \ m^3/m^2$$

A volume to surface area ratio of 0.3 m^3/m^2 means that 0.3*140=42 kg K^+ has to be transported through each square meter for a complete conversion of the bentonite to illite. With a K^+ concentration of $13*10^{-3}$ kg/m^3 a volume of 3230 m^3 groundwater per m^2 of bentonite is required for complete transformation of the bentonite to illite. For the calculated time, $t=2.7*10^5$ years, in the case of a diffusion controlled process an average of 0.012 m^3 groundwater has to pass every square meter of bentonite per year (12 l/m^2 and year). This number on the average groundwater flowrate is determined by the thickness of the bentonite barrier which is the same for the KBS-3 and VLH concepts. However it should be noted that the shrinking core equation is valid for plane geometry and the process will be faster if instead the correct cylindrical symmetry should be used. On the other hand, the assumed diffusivity for K^+ in the clay is considered to be fairly high.

Water flow in the near-field

The drifts forming a KBS-3 or VLH repository will be intersected by fractures and fracture zones. Even if parallel, these intersecting fracture zones will be connected to each other by the disturbed zone close to the drift. The question that arises is: What will limit the amount of water transported in the disturbed zone? The intersecting fracture zones or the disturbed zone itself?

Assume:

Head gradient in the direction of the drift	$\Delta p=0.003$ m/m
Distance between 2nd order fracture zones	$Z_2=500$ m
Hydraulic conductivity in 2nd order fracture zones	$K_2=10^{-8}$ m/s
Width of 2nd order fracture zone	$W_2=10$ m
Distance between 3rd order fracture zones	$Z_3=50$ m
Hydraulic conductivity in 3rd order fracture zones	$K_3=10^{-9}$ m/s
Width of 3rd order fracture zone	$W_3 = 1$ m

If the head, h_1, in a fracture zone at a point far away and at the intersection with the drift, h_2, is known then the flowrate Q can be obtained from Darcy's law for radial flow if it is assumed that the zone behaves like a homogeneous porous medium. The expression is

$$Q = K\,\frac{2\,\pi\,W\,(h_1 - h_2)}{ln\left(\frac{r_1}{r_2}\right)}$$

Where r_2 is the radius of the disturbed zone where the head is h_2 and r_1 the radial distance to a point in the zone where the hydraulic head is h1. It is further assumed that the "good" rock is impervious and that there are no other drifts nearby which acts as sinks or sources.

If the radius r_1 is taken to be 300 m, which is an arbitrary choice of distance, the flowrates that the 2nd order fracture zones can supply the disturbed zone with become

$$KBS\text{-}3\ :\ Q = 10^{-8}\,\frac{2\,\pi * 10 * 0.003 * 300}{ln\,(300/3.25)} = 1.2*10^{-7}\ m^3/s = 3.9\ m^3/year$$

$$VLH\ :\ Q = 10^{-8}\,\frac{2\,\pi * 10 * 0.003 * 300}{ln\,(300/1.5)} = 1.1*10^{-7}\ m^3/s = 3.4\ m^3/year$$

2nd order fracture zones are, however, not frequent and will be detected and can probably be grouted. If that is the case, then the 3rd order fracture zones will become important in supplying the disturbed zone with water. A similar calculation for 3rd order fracture zones gives

$$KBS\text{-}3 \;:\; Q = 10^{-9}\,\frac{2\,\pi * 1 * 0.003 * 300}{ln\,(300/3.25)} = 1.2*10^{-9}\ m^3/s = 0.039\ m^3/year$$

$$VLH \;:\; Q = 10^{-9}\,\frac{2\,\pi * 1 * 0.003 * 300}{ln\,(300/1.5)} = 1.1*10^{-9}\ m^3/s = 0.034\ m^3/year$$

These flowrates might, however, be additive if the resistance along the drift is negligible. If a 1000 m long drift is assumed, the zones entering the first half could feed the disturbed zone with water and the second half of the zones could act as outflow zones. The flow would in that case be 500/50=10 times larger in the central part of the drift than indicated in the above calculation.

If the resistance in the disturbed zone around the drift is considered, then the flow is obtained from the linear flow expression

$$Q = K * A * \Delta p$$

where K is the hydraulic conductivity in the disturbed zone and A the cross section of the disturbed zone. The flowrates will be

$$KBS\text{-}3 \;:\; Q = 10^{-8}\ \pi\left(3.25^2 - 2.25^2\right) * 0.003 + 10^{-9}\ \pi\left(6.75^2 - 3.25^2\right) * 0.003 =$$
$$= 8.5*10^{-10}\ m^3/s = 0.027\ m^3/year = 27\ l/year$$

$$VLH \;:\; Q = 10^{-8}\ \pi\left(1.5^2 - 1.2^2\right) * 0.003 + 10^{-9}\ \pi\left(3^2 - 1.5^2\right) * 0.003 =$$
$$= 1.4*10^{-10}\ m^3/s = 0.0044\ m^3/year = 4.4\ l/year$$

If the assumed numbers are valid, then the resistance in the disturbed zone is the largest and the resistance in the fracture zones has little influence on the water flow along the drift.

Illite formation due to groundwater flow in the disturbed zone

The time needed for diffusion of K^+ was found to be $2.7*10^5$ years which over this time required an average groundwater flowrate of 12 l/m^2 bentonite surface and year. The amount of groundwater that flows in the disturbed zone parallel to the drift was found to be determined by the resistance in the disturbed zone itself. The flowrates were estimated to be 27 and 4.4 l/year respectively, for the KBS-3 and VLH. Water will flow parallel to the drift in both the KBS-3 and VLH and to determine whether the conversion of bentonite to illite is controlled by either diffusion or the amount of groundwater flowing in the disturbed zone some kind of contact area has to be assumed.

If it is assumed in the KBS-3 concept that all K^+ that is transported with the groundwater in the disturbed zone, 13 mg/l and 27 l/year, will participate in the conversion of bentonite to illite in the deposition holes, the following flowrate per square meter will be obtained

$$\frac{27\ l/year}{\pi * d * L} = \frac{27\ l/year}{\pi * 1.6 * 6.9} = 0.8\ l/m^2 \text{ and year}$$

This number is probably very conservative since it is assumed that all K^+ in the groundwater in the disturbed zone around the tunnel participate in the conversion of bentonite into illite in the deposition hole.Furthermore, it has in the discussion above been assumed that all K^+ present in the groundwater will participate in the conversion of bentonite in a single deposition hole even though the deposition holes will be located in a row along the tunnel. The flowrate is still considerably lower than the 12 l/year and m^2 bentonite surface that is required if the conversion process should be controlled by diffusion.

Because of the geometry there is a difference in making an estimation for the VLH concept since K^+ have to be transported perpendicular to the groundwater flow direction to convert bentonite into illite. The circumference of a VLH drift is π*2.4=7.5 m and the groundwater flow rate in the disturbed zone is estimated to be 4.4 l/year. If it is assumed that all K^+ present in the water will be taken up within a one meter section of the drift, then the average flow within this one meter section would be

$$\frac{4.4\ l/year}{7.5*1} = 0.6\ l/m^2 \text{ and year}$$

This number should be compared with the groundwater flow required if the process should be controlled by diffusion which was found to be 12 l/year and m^2.

Conclusions

If the conversion of bentonite to illite should be controlled by diffusion of K^+ the process would take $2.7*10^5$ years even though the assumed diffusivity is considered to be high. However, estimations indicate that the amount of water flowing in the vicinity of the drifts will be the limiting factor. The time needed for complete conversion of bentonite into illite is dependent on the surface area of buffer material in contact with groundwater containing K^+, but is expected to be order(s) of magnitude larger than the time it would take if the conversion process should be controlled by diffusion.

Appendix 3

Hydrogen formation and release from an ACP-canister

This appendix examines the possibility of the formation of a gas section in the upper part of an ACP-canister with a penetration hole at the welding in the top of the canister. The question is at what corrosion rate will gas accumulate in the canister because of a higher rate of formation for hydrogen than the release by diffusion.

Known data:
Inner surface area of canister A= 10.3 m^2
Concentration of dissolved hydrogen C=10.8 mol/m^3 (at 5 MPa)
Diffusivity of hydrogen in bentonite De=2.2 10^{-11} m^2/s
molar weight of iron M_{Fe}=55.8 10^{-3} kg/mol
Density of iron ρ=7.86 10^3 kg/m^3

Calculate the corrosion rate x at which the produced hydrogen can be released by diffusion.

Diffusion rate out from canister

$$N_{diff} = D_e \Delta C \pi d_h$$

Formation rate of hydrogen

$$N_{corr} = \frac{4}{3} \frac{A_{can} x \rho}{M_{Fe}}$$

if $N_{diff} = N_{corr}$ then

$$x = \frac{3}{4} \frac{D_e \Delta C \pi d_h M_{Fe}}{A_{can} x \rho}$$

If the penetration hole is assumed to be cylindrical with a diameter of 10 mm gas will accumulate if the corrosion rate is larger than 5 10^{-10} m/year which is much lower than can be expected. Thus it is very likely that gas will prevent the diffusion of the radionuclides since a penetration hole would most likely be smaller than is assume in the calculation above and the corrosion rate would probably be larger than 5 10^{-10} m/year.

Appendix 4

Advection of water from a penetrated canister due to pressure buildup from hydrogen

A copper-steel canister that has an initial defect will become filled with water and radionuclides may be leached from the fuel. The release of radionuclides is limited by the diffusion from the inside of the canister through the penetration hole and into the bentonite backfill if no pressure buildup inside canister can cause significant advection through the penetration hole. This appendix examines in a very simplified manner the possible rate of advection from both a KBS-3 and a VLH canister. Both canister types are assumed to have the hole located at the lowest part and the corrosion is assumed to take place over the whole inside area and this area is assumed to be constant with time. The steel is approximated with 100 % iron .

Data used for both concepts

Hydraulic conductivity in bentonite K_b	$= 1\cdot10^{-12}$ m/s
Corrosion rate x	$= 1\cdot10^{-6}$ m/year
Gas constant	= 8.31
Initial pressure inside canister	$= 1\cdot10^{5}$ Pa
Near field pressure	$= 30\cdot10^{5}$ Pa
Hole diameter	$= 1\cdot10^{-2}$ m
Temperature	= 373 K
molar mass of iron M_{Fe}	$= 55.8\ 10^{-3}$ kg/mol
Density of iron ρ	$= 7.86\ 10^{3}$ kg/m^3

4/3 mol of hydrogen is formed by the corrosion of 1 mol if iron

KBS-3 Specific data

Canister diameter = 0.68 m

Void volume unfilled canister = 1.2 m^3

Inner surface area of canister A_{can} = 10 m^2

VLH Specific data

Canister diameter = 1.28 m

Void volume unfilled canister = 6 m^3

Inner surface area of canister A_{can} = 22 m^2

Analogous to the steady state diffusion rate through the penetration hole described in Appendix 3 the flow of water into or out from the canister Q_v is approximated with

$$Q_v(t) = K_b \Delta h(t) \pi d_h$$

and thus the flowrate will be proportional to the head difference(Δh) because the hydraulic conductivity and the hole diameter is assumed to be constant with time.

The formation rate of hydrogen is calculated as

$$N_{corr} = \frac{4}{3}\frac{A_{can} x \rho}{M_{Fe}}$$

The equations were solved numerically with the Runge-Kutta method and the water flowrates and water volume inside the canister are shown in Figures A4-1 and A4-2 for the KBS-3 canister and in Figures A4-3 and A4-4 for the VLH-canister. Flow rates with a negative sign denotes flow into the canister. The maximum flow rates are rather similar and about 0.25 l/year. The release from the VLH-canister is slightly larger due to the larger corrosion area. The assumption that an initial penetration hole is located at the bottom of the canister is extremely unlikely for the KBS-3 canister but this hole position can not be ruled out for a canister with a horizontal positioning as in the VLH-concept. The more likely location for an initial damage to a KBS-3 canister is at the welding of the lid and as was shown in Appendix 3 the formation of hydrogen will most likely result in the formation of a gas filled section which would limit both the amount of radionuclides that can be released by diffusion as well as by advection.

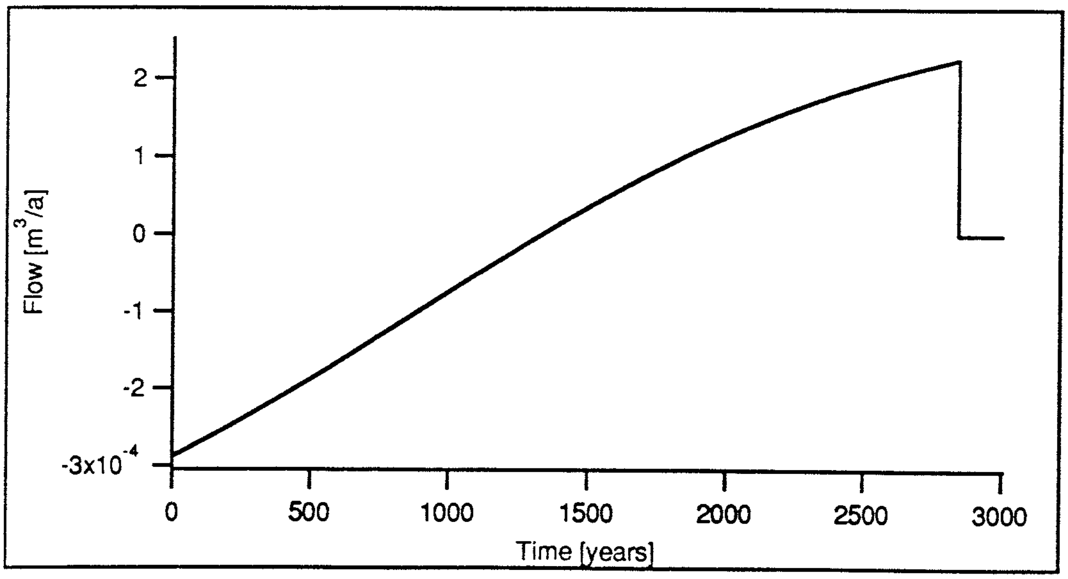


Figure A4-1. Water flowrate into and out of a KBS-3 canister. Negative values denote flow into the canister.

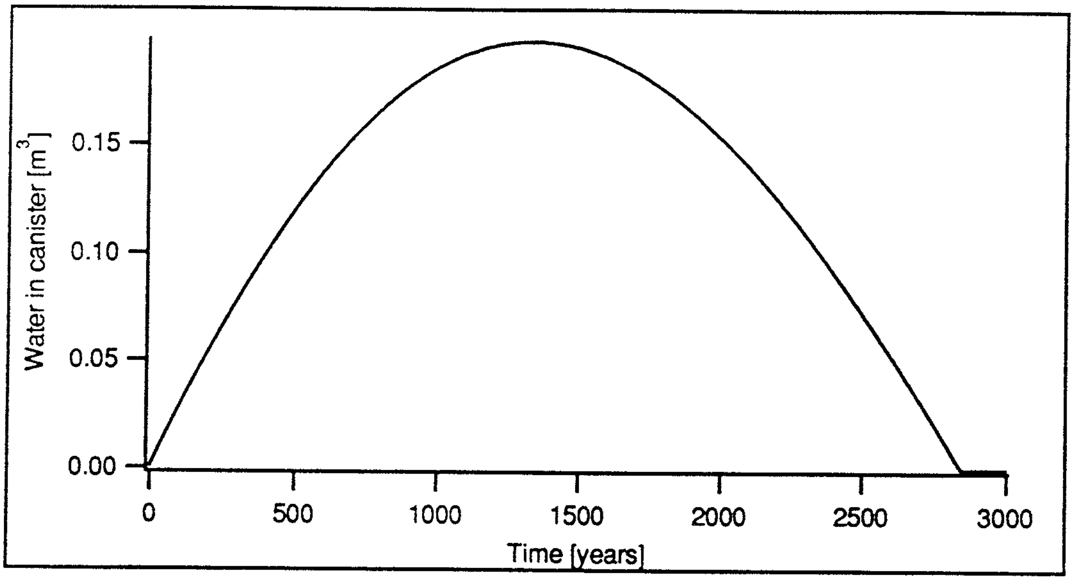


Figure A4-2. Water volume inside a KBS-3 canister as function of time.

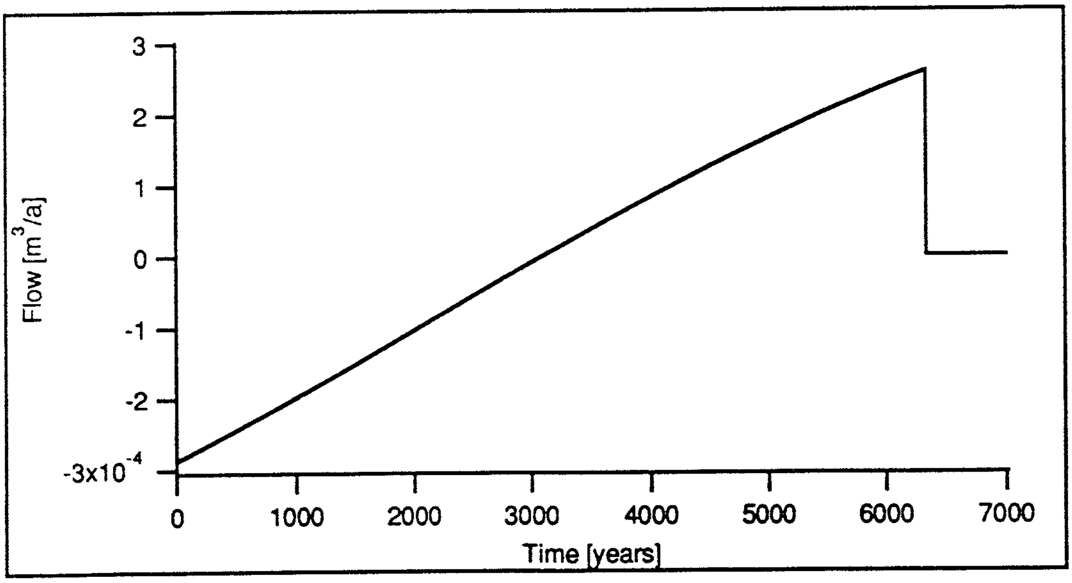


Figure A4-3. Water flowrate into and out of a VLH canister. Negative values denote flow into the canister.

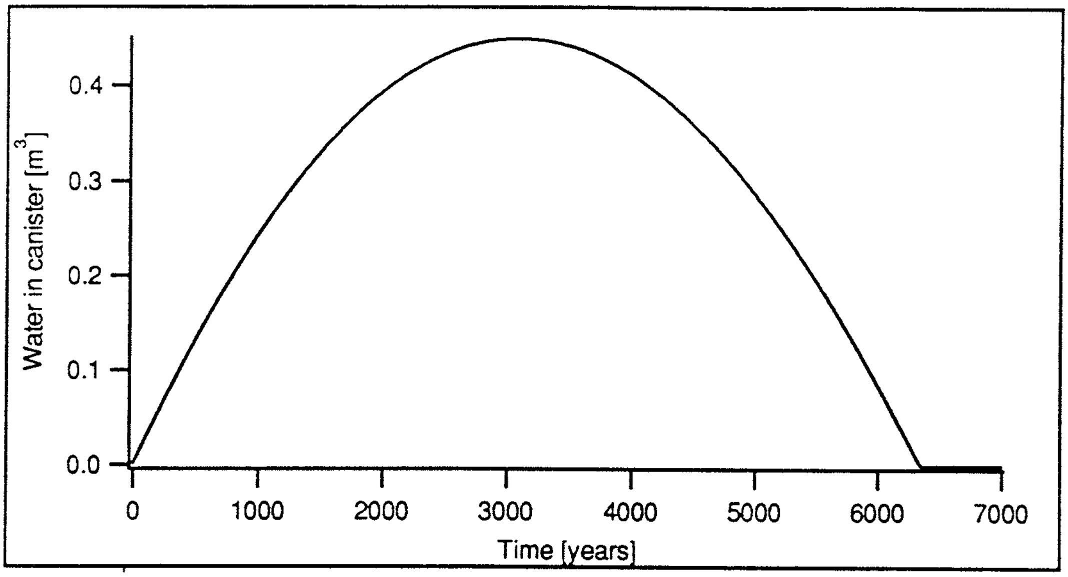


Figure A4-4. Water volume inside a VLH canister as function of time.

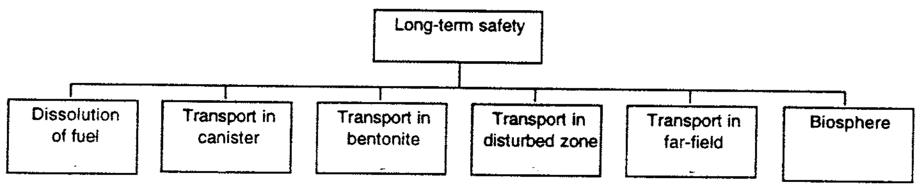
The value of the hydraulic conductivity of the bentonite used in the calculations is quite high and the assumed diameters of the hole is quite large. Using a ten times lower hydraulic conductivity and hole with a diameter of 0.0025 m, yield a release rate of water through the bentonite less then 0.01 l/year.

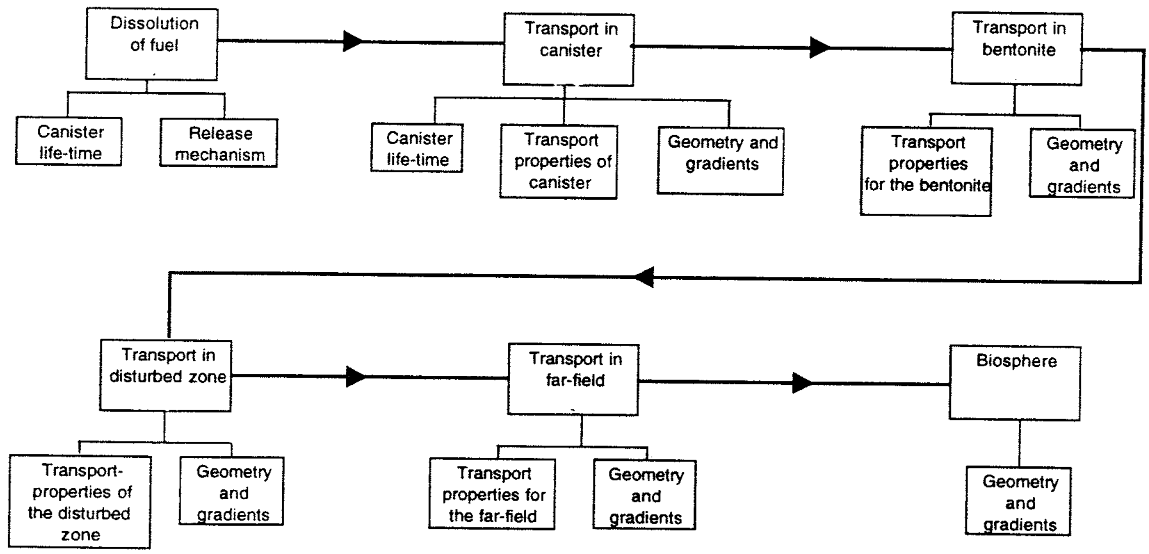
For comparison, the equivalent flowrate for diffusion dominated release through the bentonite was calculated assuming the larger hole diameter, 0.01. With a diffusivity of 10^{-10} m^2/s this flowrate is 0.1 l/year, which is in the same range as the water flow rate due to displacement by gas, 0.25 l/year.

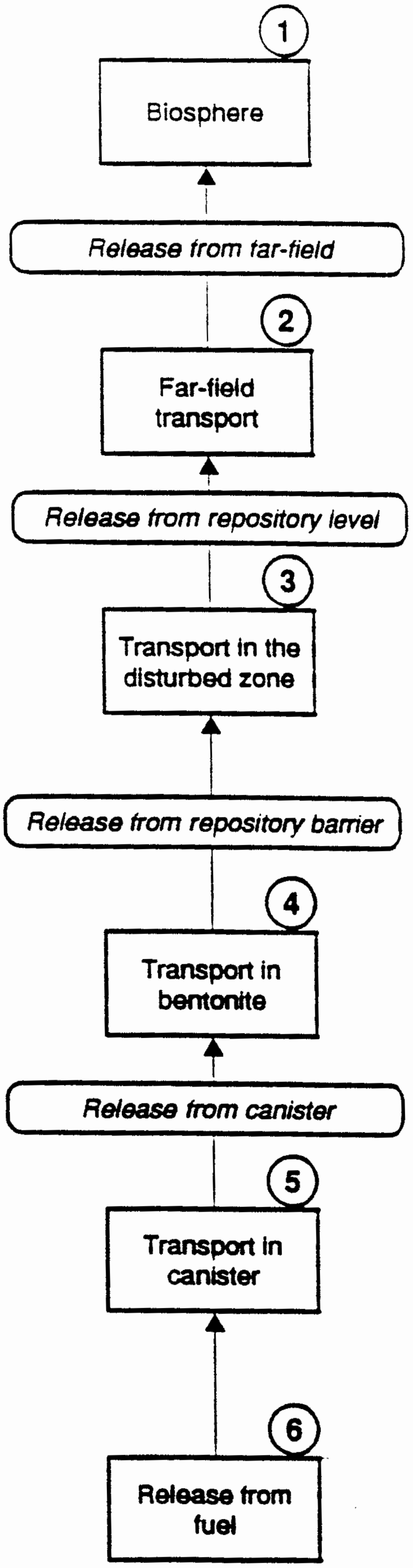
Appendix 5

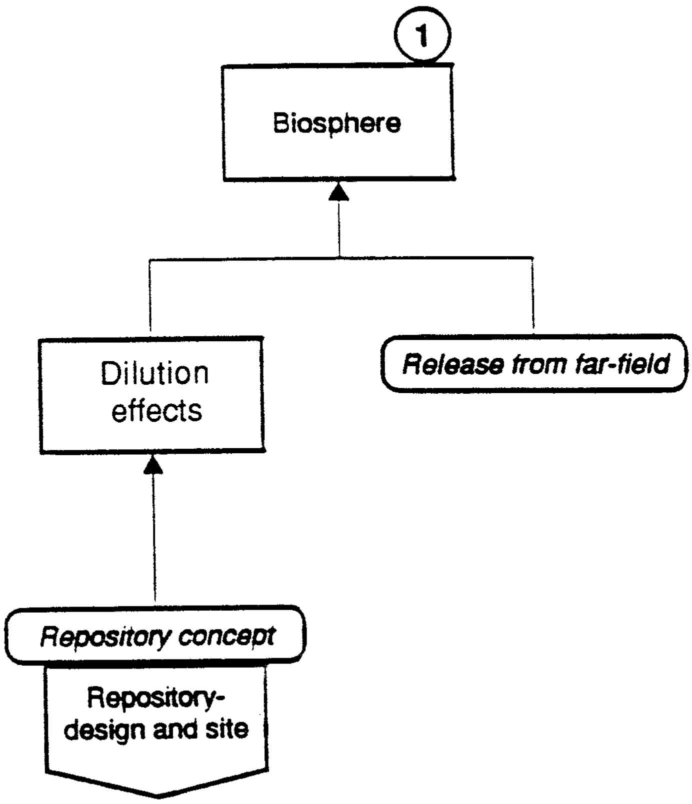
Assessment system

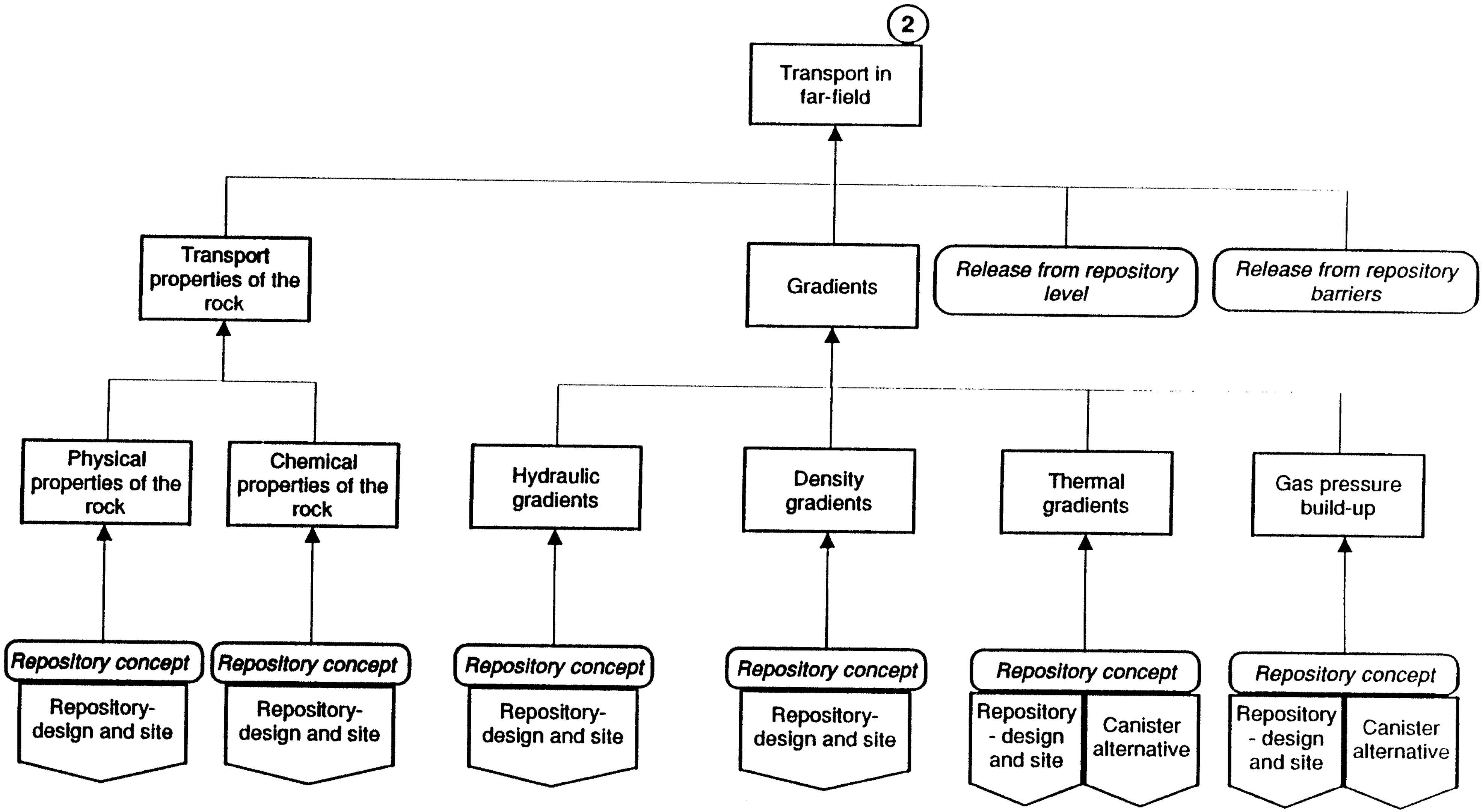
In this appendix a number of illustrations of the assessment system is presented. First an overview illustration of areas influencing the long-term safety is shown and the following pictures show more detailed dependencies.

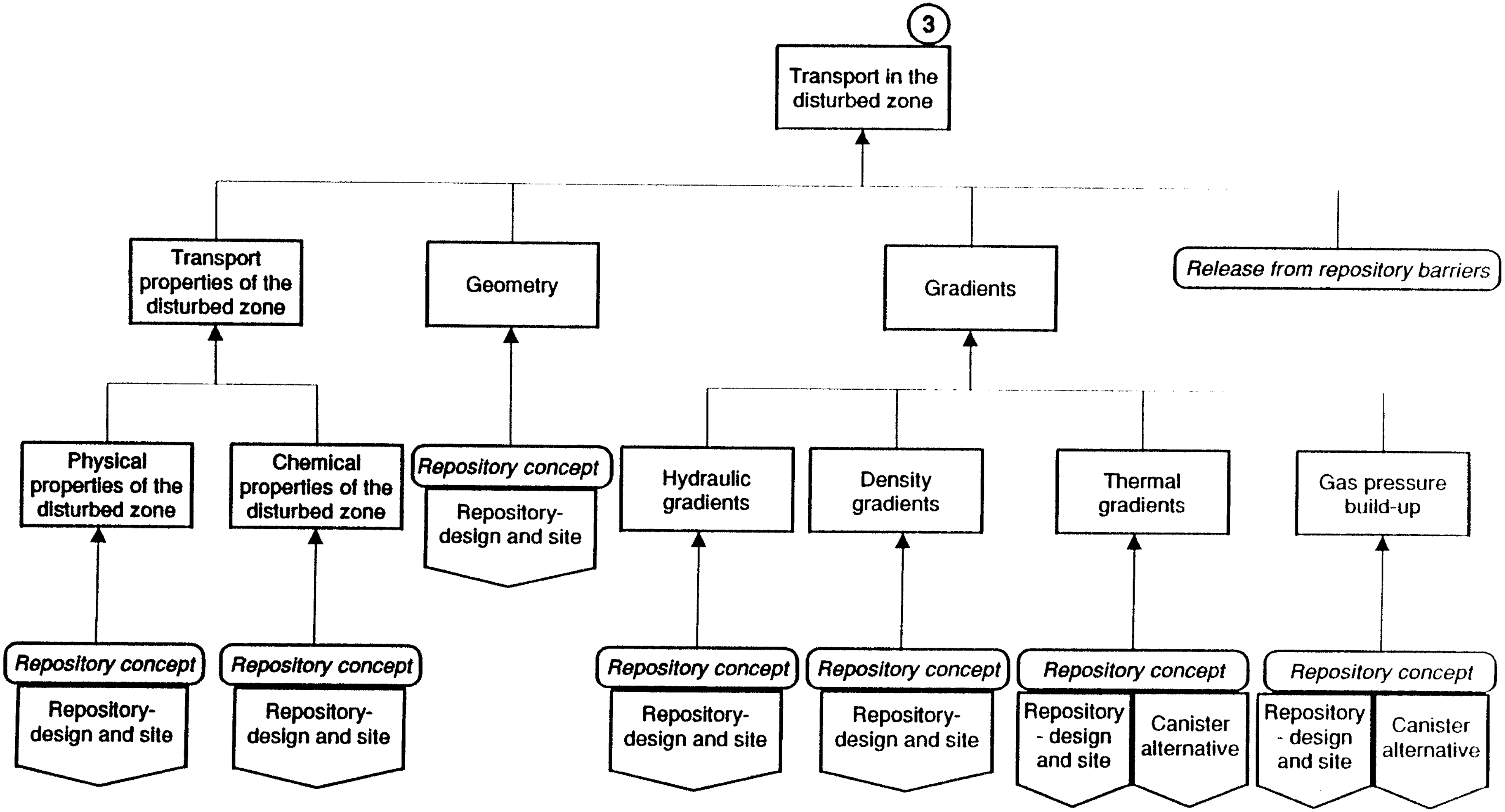





1
Biosphere
Release from far-field
2
Far-field transport
Release from repository level
3
Transport in the disturbed zone
Release from repository barrier
4
Transport in bentonite
Release from canister
5
Transport in canister
6
Release from fuel


1
Biosphere
Dilution
effects
Release from far-field
Repository concept
Repository-
design and site


2
Transport in far-field
Transport properties of the rock
Gradients
Release from repository level
Release from repository barriers
Physical properties of the rock
Chemical properties of the rock
Hydraulic gradients
Density gradients
Thermal gradients
Gas pressure build-up
Repository concept
Repository-design and site
Repository concept
Repository-design and site
Repository concept
Repository-design and site
Repository concept
Repository-design and site
Repository concept
Repository - design and site
Canister alternative
Repository concept
Repository - design and site
Canister alternative


3
Transport in the disturbed zone
Transport properties of the disturbed zone
Geometry
Gradients
Release from repository barriers
Physical properties of the disturbed zone
Chemical properties of the disturbed zone
Repository concept
Repository-design and site
Hydraulic gradients
Density gradients
Thermal gradients
Gas pressure build-up
Repository concept
Repository-design and site
Repository concept
Repository-design and site
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Repository-design and site
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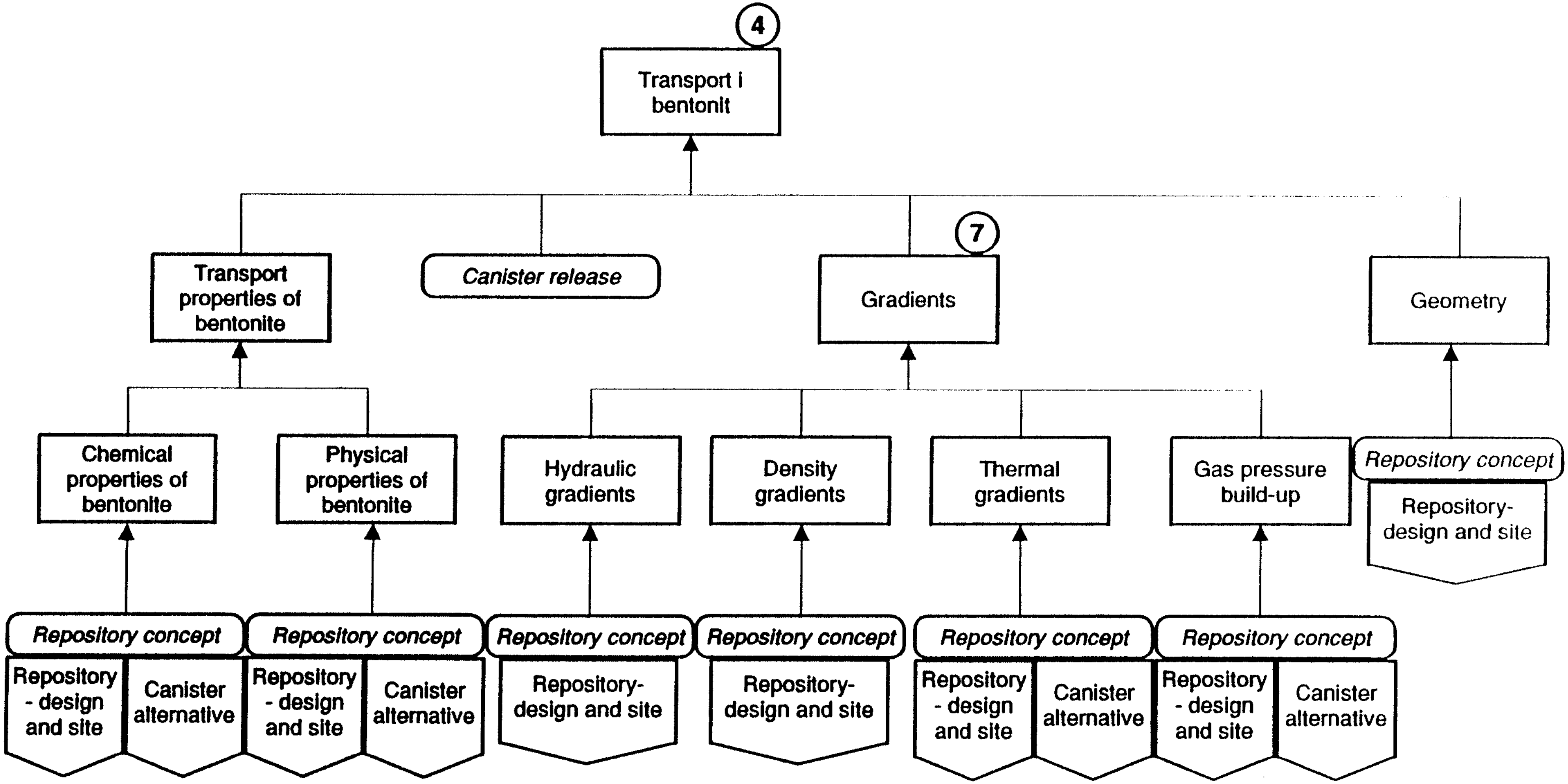
Repository concept
Repository - design and site
Canister alternative
Repository concept
Repository - design and site
Canister alternative


4
Transport i bentonit
Transport properties of bentonite
Canister release
7
Gradients
Geometry
Chemical properties of bentonite
Physical properties of bentonite
Hydraulic gradients
Density gradients
Thermal gradients
Gas pressure build-up
Repository concept
Repository- design and site
Repository concept
Repository - design and site
Canister alternative
Repository concept
Repository - design and site
Canister alternative
Repository concept
Repository- design and site
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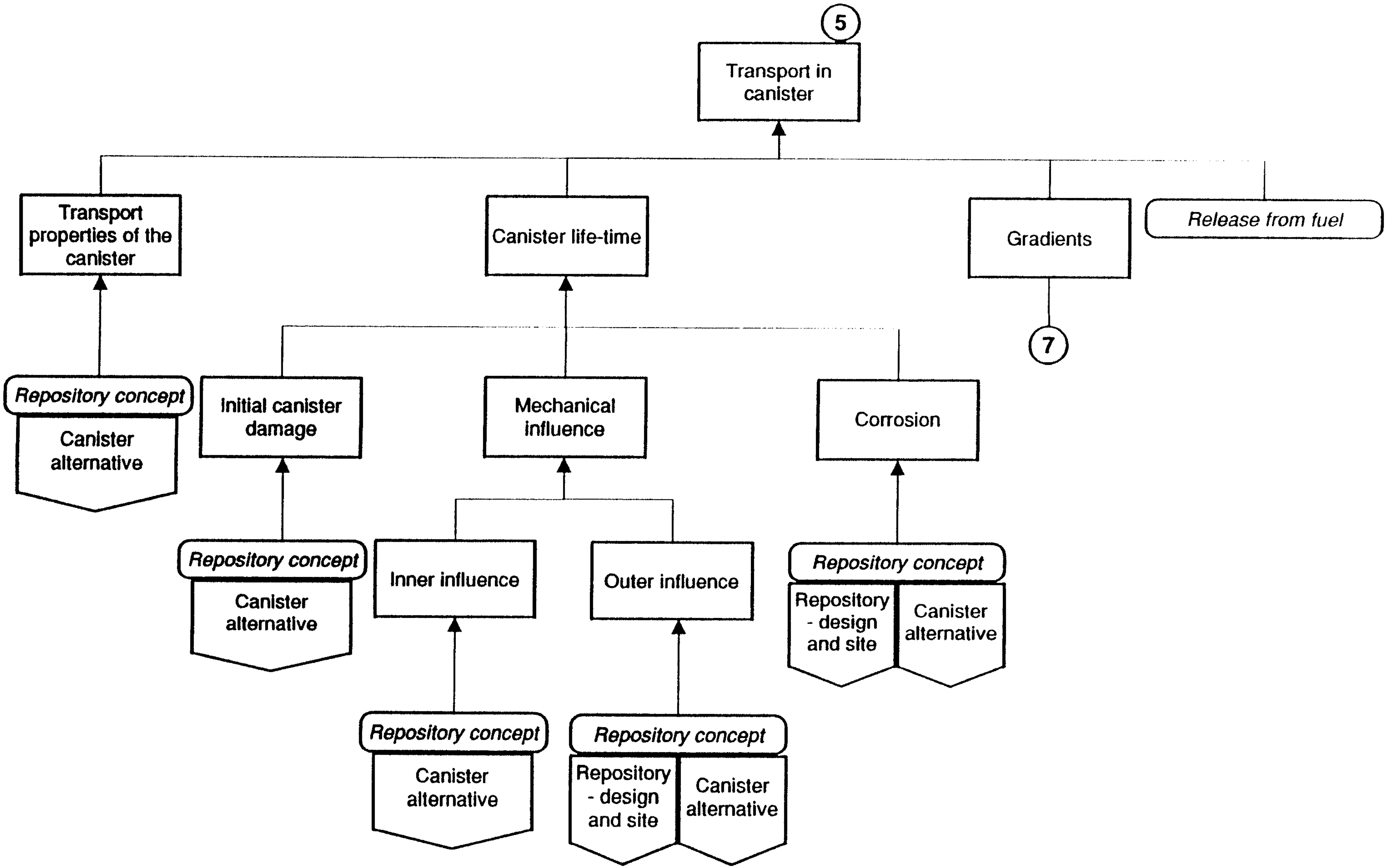
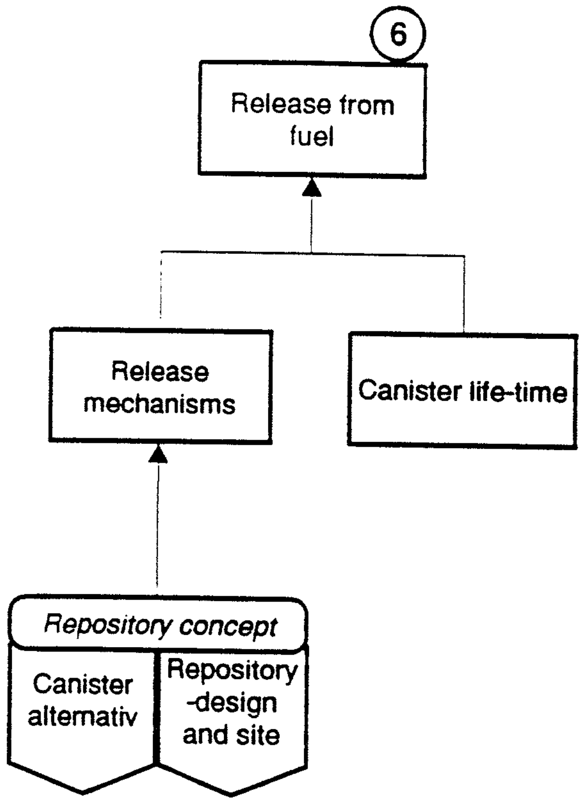
Repository - design and site
Canister alternative
Repository concept
Repository - design and site
Canister alternative



5
Transport in canister
Transport properties of the canister
Canister life-time
Gradients
Release from fuel
7
Repository concept
Canister alternative
Initial canister damage
Mechanical influence
Corrosion
Repository concept
Canister alternative
Inner influence
Outer influence
Repository concept
Repository - design and site
Canister alternative
Repository concept
Canister alternative
Repository concept
Repository - design and site
Canister alternative


6
Release from fuel
Release mechanisms
Canister life-time
Repository concept
Canister alternativ
Repository -design and site

Appendix 6

Compilation of geological and geochemical background data

TABLE OF CONTENTS APPENDIX 6

1 GEOLOGY

1.1 General

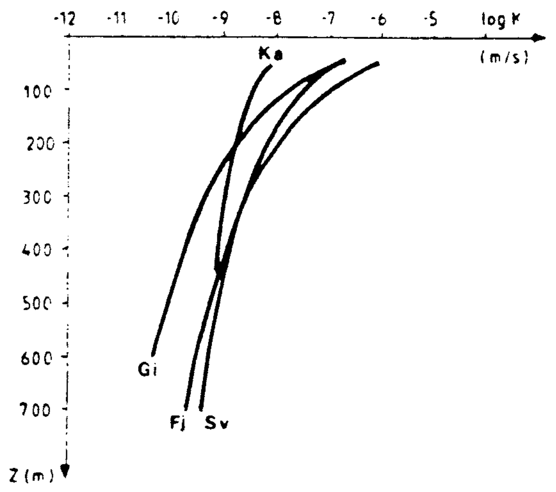
This Appendix gives a general description of geological and geochemical conditions at depths relevant for the alternative repository concepts.The repository is proposed to be located at the 500 m level for the KBS-3, VLH and MLH concepts, while the canisters in the VDH concept will be located at the 2000-4000 m level. The presented information for rock located at about 500 m depth is compiled from measurements performed at Fjällveden, Gideå, Kamlunge, Sternö, Finnsjön and SFR *[Ahlbom, 1991]* and Finnsjön, SFR and Stripa *[Pusch et al., 1991]*. The geological description for the VDH concept is based on Juhlin and Sandstedt [*1989*]. The amount of information regarding depths relevant for the VDH concept (2000-4000 m) is however very sparse, especially from Sweden where information only is available from a single borehole in the Siljan ring area, why the geological and geochemical conditions for this alternative can not be described in the same detail as for the other concepts which are proposed to be located at 500 m depth.

Firstly, the variation of rock properties with depth is presented. The hydraulic conductivity and temperature variations with depth are given in Section 1.2 and the variations in geochemical conditions in Section 1.3. Finally, the host rock characteristics defined for the repository concepts are given in Section 1.4 to 1.5.

1.2 Geological conditions variation with depth

1.2.1 Hydraulic conductivity as function of depth

The variation in hydraulic conductivity with depth has been studied at some of the KBS-3 sites down to depths of about 700 m. The tested sections were divided into fracture zones and rock mass. Each of these "rock types" were treated individually when determining the hydraulic conductivity variation with depth.The overall trend is that the hydraulic ɔnductivity for local fracture zones as well as for the rock mass decreases with increasing ɔth, see Figure A6-1.



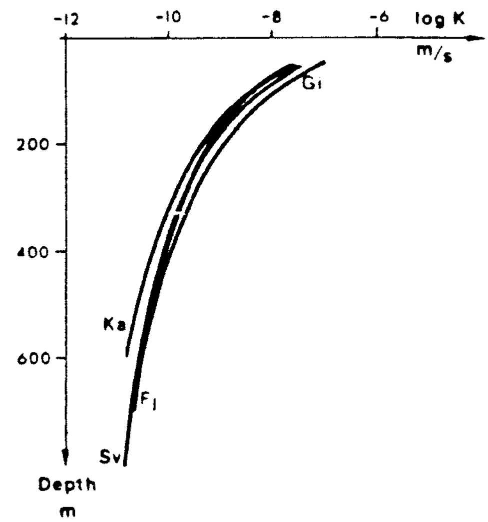


Figure A6-1. Calculated relations between depth and hydraulic conductivity in local fracture zones and the rock mass. Fj=Fjällveden, Gi=Gideå, Km=Kamlunge and Sv=Svartboberget.

The hydraulic conductivity decreases rapidly the first 200-300 m in local fracture zones as well as in the rock mass. The hydraulic conductivity at 500 m depth is about 10^{-9} m/s for the local fracture zones and about 10^{-10} m/s in the rock mass.

A compilation of the permeability as function of depth from deep boreholes located in crystalline rocks in USA, Germany, France, Switzerland, United Kingdom, CIS and Sweden is given in Figure A6-2. It should be noted that the permeabilities have been measured over fairly extensive intervals (approximately 25 m) and the rock within these intervals may be highly variable.

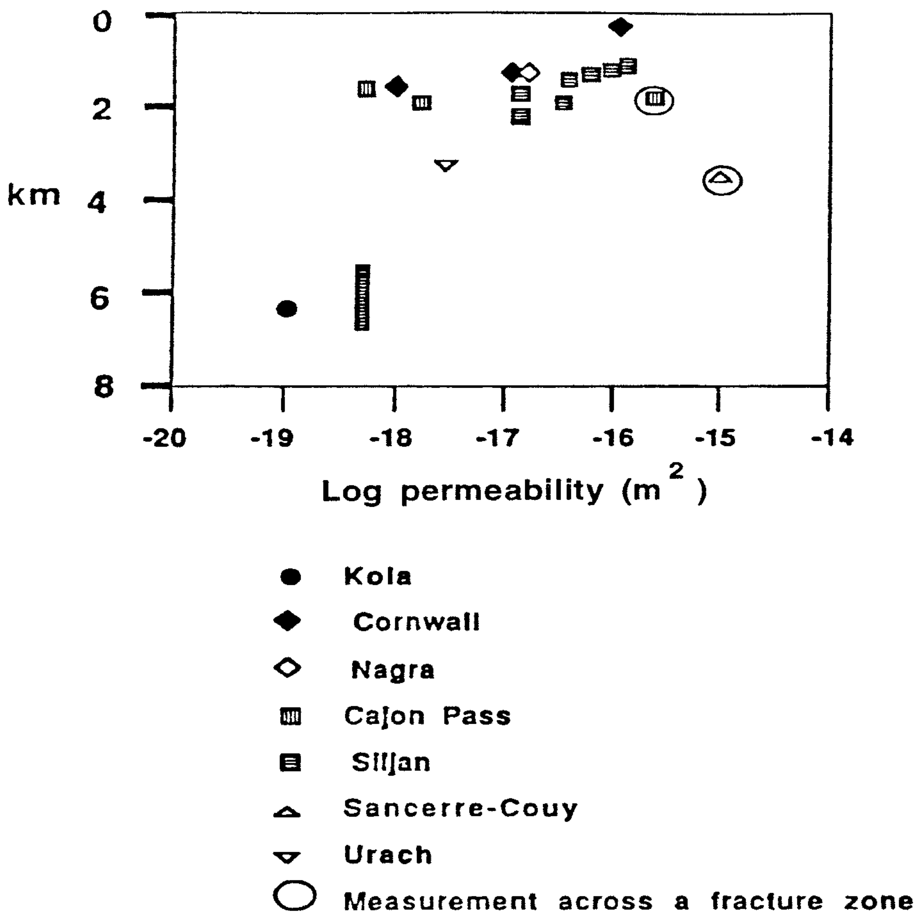


Figure A6-2. Permeability estimates in deep boreholes.

There is a trend towards lower permeabilities with depth with a few exceptions. These two exceptions may, however, be viewed as being representative of permeabilities for fracture zones while the other values may be viewed as being representative for the rock mass. The permeabilities measured at Siljan appear to be typical for crystalline rock. All data should be taken with some caution, since the permeability measured may vary with the differential pressure applied [*Pine and Ledingham, 1983*].

1.2.2 Temperature as function of depth

The temperature has been measured in three sub-vertical boreholes at the Finnsjön site down to about the 500 m level. The temperature increases with increasing depth and the gradient was found to be 1.3 °C/100 m. The absolute temperature at the 500 m level was found to be 12.3 °C.

The temperature gradient was found to be 1.61 °C/100 m, from the surface down to about 600 m depth, in two series of measurements in borehole Gravberg-1 . This value on the temperature gradient is larger than found in the shallower Finnsjön boreholes. The difference can be explained by the cooling effect from the ice cover during the last period of glaciation or on circulation of surface waters. Including the findings from other deep boreholes it is found that the temperature gradient varies between 1.3-9 °C/100 m, with a typical value close to 3 °C/100 m [*Juhlin and Sandstedt, 1989*].

1.3 Geochemical conditions, variation with depth

1.3.1 Groundwater composition, change with depth

There are a number of investigation of the variation in groundwater composition with depth [*Ahlbom et al., 1989 and Laaksoharju, 1990a, b*] covering depths from surface down to about 800 meters. The Stripa data are not representative for crystalline rock due to the presence of the iron ore in this earlier operated mine.

Of the ten measurements made at Gideå only two were considered to be representative for the sampled depth so no conclusion regarding depth dependence can be made from this site [*Ahlbom et al, 1991*]. Investigations of the groundwater chemistry was also made at Fjällveden both for KBS-3 [*1983*], [*Laurent, 1983*] and later investigations [*Wikberg et al., 1985*]. As in the Gideå measurements very little could be said about the depth variations. For greater depths the information is more scarce but a compilation of measurements on salinity at different depths is available in [*Juhlin and Sandstedt, 1989*]. The most important parameters that influence the groundwater composition are pH and Eh. When values of these two variables change with depth the water chemistry is also altered. The dissolved species can be divided into three groups categorized according to whether the element concentrations in general are decreasing, increasing or are constant with depth. The category into which an element belongs is an indication of the origin of the element. Below, the elements which are of interest are grouped in this way.

Increasing:
The concentration of the elements Cl, Br, Na, Ca, SO_4, Sr, Li and Al are often increasing with depth.

Decreasing:
The concentrations of HCO_3, Mn, Mg, D, Fe (II), Fe(tot), NH_4,TOC (total organic carbon) are decreasing with increasing depth.

Constant:
The concentrations of Si, Al, K, PO_4, I, Tritium, NO_2, NO_3 are slightly varying or constant with depth.

An example of the variation in concentrations for a number of species from the Finnsjön investigation is shown in Figure A6-3.

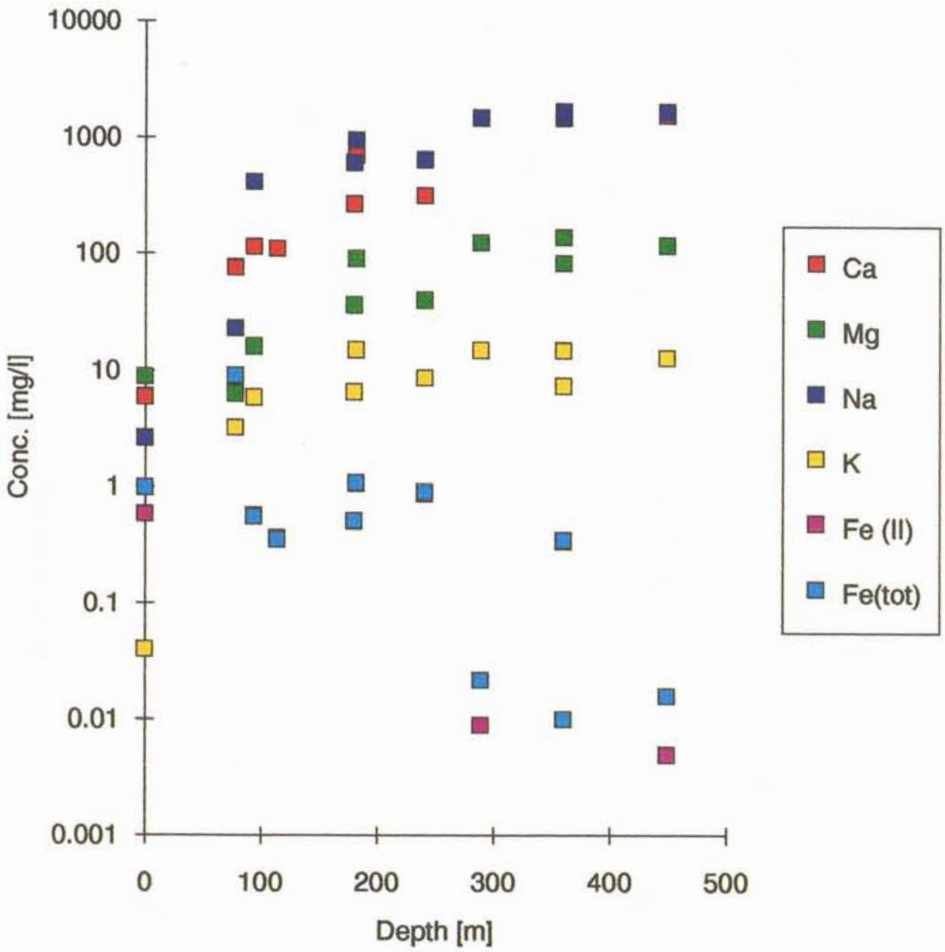


Figure A6-3. Variation in groundwater composition with depth from measurements at Finnsjön.

1.3.2 Groundwater salinity, change with depth

As mentioned in Section 2.3.3 the concentration of Cl in the water samples taken is increasing with increasing depth. In Figure A6-4 the variation with depth of Cl and Na in water samples taken at Finnsjön in two different bore holes is presented.

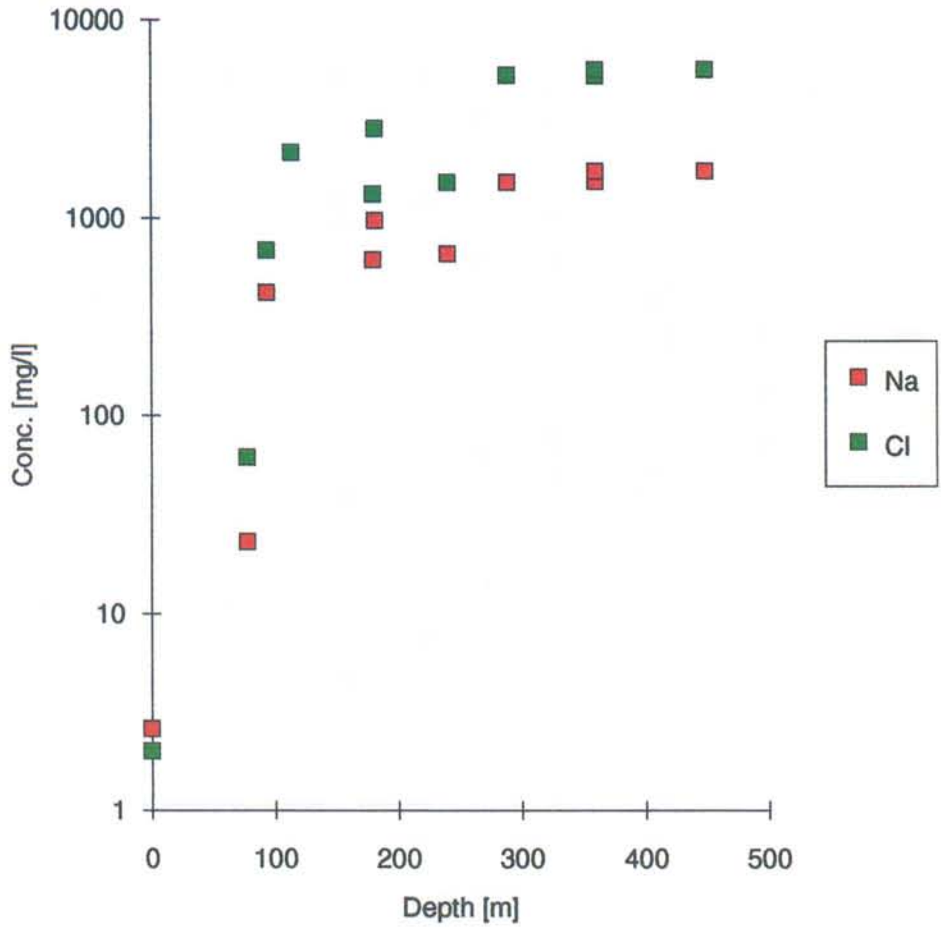


Figure A6-4. Variation in Na and Cl with depth from measurements at Finnsjön.

Investigations on waters at greater depths have also been performed [*Juhlin and Sandstedt, 1989*] but the data are limited to the salinity values.There is a trend towards increasing salinity with depth, particularly in the Kola borehole. Figure A6-5 illustrates the salinity as function of depth for these deep boreholes.

Due to operational problems it was not possible to determine the exact depth of the water samples. Since the well was hydro-fractured downward below its total depth it is possible that these fluids originate from as deep as 7500 m. The sampled water had high concentrations of salts, about 40000 ppm Ca^{+} and 12000 ppm Na^{+} with Cl^{-} being the major anion.

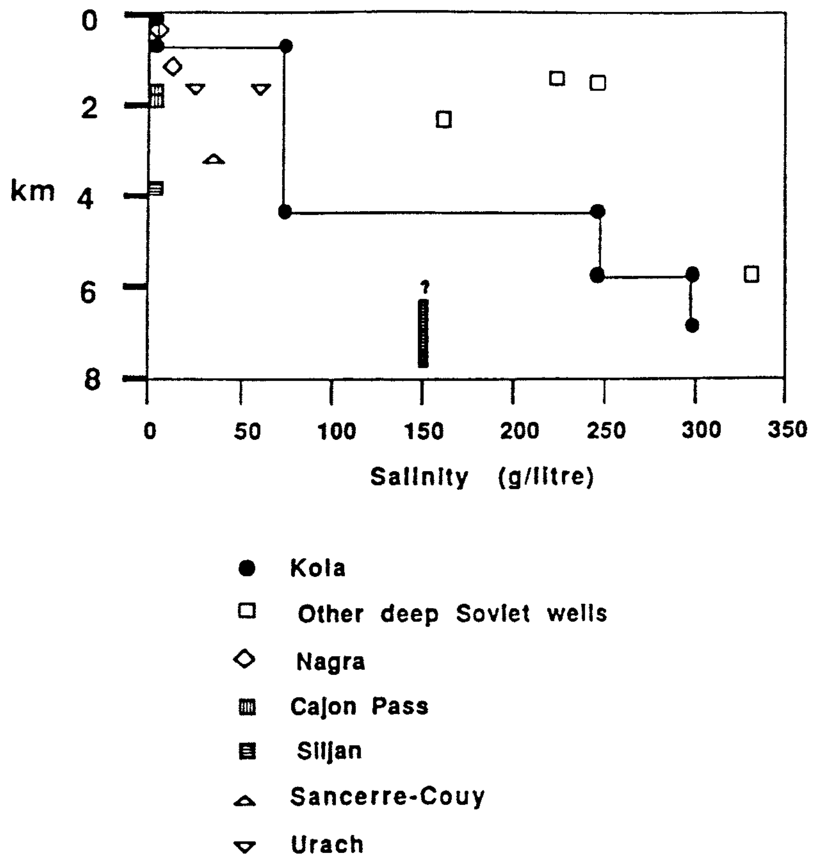


Figure A6-5. Salinity of formation waters from deep crystalline boreholes.

In summary the geochemical conditions will vary with depth. The expected trends of decreasing permeability and increasing salinity with depth appear to be verified by drilling, however, data are sparse. In addition, results from several boreholes prove that open fracture zones can exist at depths below 2000 m and that they can be water carrying.

1.4 Host rock description at 500 m level

A description of a reference site regarding geological and hydraulic characteristics is needed to compare the different concepts . This description for the 500 m level is based on the significant amounts of geological information that have been collected from measurements in Fjällveden, Gideå, Kamlunge, Sternö, Finnsjön, Stripa and SFR [*Ahlbom, 1991, Pusch et al. 1991*]. The following chapter will describe typical rock at the 500 m level based on the above mentioned investigated sites. The sites consist of either granite or gneiss.

The compilation is mainly based on work by Ahlbom [*1991*] and Pusch et al. [*1991*] . Both these works are based on essentially the same information obtained from sites studied within the SKB-program, but have different ambitions and differ somewhat in estimated hydraulic conductivities for the discontinuities. The description regarding larger discontinuities, fracture zones, are quite similar if frequency and widths are considered, but the hydraulic conductivities are estimated to be about one order of magnitude higher in the study by Pusch et al., one reason being that pusch et al. also consider characteristics of site, which have been investigate in conjunction with different industrial projects. The

Pusch et al. study is therefore considered to give fairly conservative values with respect to expected characteristics of spent fuel repository sites.

The smallest discontinuities considered in the Ahlbom study [*Ahlbom, 1991*] are fractures with a spacing of about 0.5 m. The rock in between these fractures is lumped as "surrounding rock mass" and given an average hydraulic conductivity. Pusch et al. [*1991*] include discontinuities as small as interconnected voids located at the junction points of adjacent crystals.

The following compilation includes findings from both these mentioned studies and the difference in estimates of hydraulic conductivities is summarized in Table A6-1.

1.4.1 Fracture zones

The observed fracture zones have been classified into different orders dependent on their characteristics [*Ahlbom, 1991*]:

Regional fracture zones	(1st order)
Local fracture zones	(2nd order)
Minor intrablock fracture zones	(3rd order)
Subhorizontal fracture zones	(orders unknown)

An estimate of the distance between fracture zones for a given order is dependent on dominating fracture zone directions. The spacings have therefore been estimated for two directions: perpendicular and parallel to the dominating set of fracture zones.

Regional fracture zones (1st order)

Lineaments of lengths more than 4 km which are topographically well expressed, have at the investigated sites been interpreted as regional fracture zones. These zones may have extensions of many tens of kilometers and usually form a more or less distorted orthogonal pattern [*Ahlbom, 1991 and Pusch et al., 1991*]. A few of these lineaments have been penetrated with boreholes indicating steeply dipping fracture zones of 50-150 m widths. These regional fracture zones are strongly fractured, clay altered and water conductive.

Studies of topographical maps from the investigated sites gave the following spacings [*Ahlbom, 1991*]:

Perpendicular:	3.2 km (span: 2.4-3.7 km)
Parallel:	6.9 km (span: 4.9-9.1 km)

The variation in spacing between fracture zones is surprisingly small both perpendicular and parallel to the dominating set of fracture zones. Rock blocks with typical sizes of approximately 3 km * 6 km and not intersected by any regional fracture zone seem to be possible to find at any of the investigated sites. It therefore seems reasonable to assume that the regional fracture zones could be avoided within a repository site if the length is limited to one or a few km, but these fracture zones might influence the migration of radionuclides in the far-field which is discussed in Chapter 4.

These regional fracture zones are estimated to have hydraulic conductivities of 10^{-7} m/s [*Ahlbom, 1991*], 10^{-6} m/s [*Pusch et al., 1991*].

Local fracture zones (2nd order)

The 2nd order local fracture zones have been interpreted from air-photos and ground geophysical surveys. These local fracture zones intersect the rock blocks defined by the regional 1st order fracture zones. Most interpreted zones have been penetrated with boreholes giving dip, geologic and hydraulic characteristics.

These local fracture zones have widths varying between 1-20 m and have extensions generally assumed to be several hundreds of meters up to some kilometers. Most of these zones dip 60-90° from the horizontal plane. Although a general increase in fracturing is associated with these fracture zones, the strongly fractured parts are often less than 0.1 m. The local fracture zones usually do not give any major stability problems during tunnel excavation.

Studies of air-photos and detailed ground geophysical surveys from the investigated sites gave the following spacings [*Ahlbom, 1991*]:

Perpendicular:	0.4 km (span: 0.3-0.6 km)
Parallel:	0.8 km (span: 0.3-1.4 km)

The variation in spacing is small perpendicular to the dominating set of fracture zones. The variation is, however, larger parallel to the dominating set of fracture zones.

It seems reasonable to assume that local fracture zones can not be avoided within a repository site. One or a few of these zones will probably intersect a repository and will thereby represent important flowpaths for radionuclides.

These local fracture zones are estimated to have hydraulic conductivities of: 10^{-8} m/s [*Ahlbom, 1991*], 10^{-7} m/s [*Pusch et al., 1991*].

Minor intrablock fracture zones (3rd order)

These 3rd order fracture zones have been described at two sites, SFR and Stripa. In SFR these fracture zones have been found to have a spacing of about 100 m. Investigations in the Stripa mine have indicated spacings of 50-70 m and typical widths of 0.5-2 m [*Ahlbom, 1991*]. At both investigated sites these 3rd order fracture zones are associated with some increase in the hydraulic conductivity. These 3rd order discontinuities, which serve as major transmissive fracture zones in repositories because of their frequency and conductivity, are supposed to extend for up to several hundred meters [*Pusch et al., 1991*].

Because of limited amount of available data on the existence and characteristics of the 3rd order fracture zones all estimates are to be considered as highly uncertain. The spacing between the zones are assumed to be 100 m until more accurate information is available.

These 3rd order fracture zones are estimated to have hydraulic conductivities of: 10^{-9} m/s [*Ahlbom, 1991*], 10^{-8} m/s [*Pusch et al., 1991*].

Fractures (4th order)

The fracture spacing at the 500 m level has been estimated from surveys on outcrops and in tunnels as well as from drill cores. Even though some of these investigations have been performed at the surface, the spacings should be valid also for the 500 m level since fractures today observed at the surface as well as at the 500 m level have been formed under similar conditions at significant depths [*Ahlbom, 1991*].

Due to differences in the mapping technique, the spacings between fractures are about twice as large for outcrops. Fractures shorter than 0.5 m are excluded when mapping outcrops. The fracture spacing, measured on outcrops, is 0.8-1.1 m for all investigated sites except for Finnsjön and SFR where the fracture spacing is found to be 0.2-0.3 m. The obsereved fracture spacings are:

Outcrops:	0.8 m (span: 0.2-1.1 m)
Drill cores:	0.4 m (span: 0.2-0.6 m)

Data from SFR indicate that the ratio between conductive and total number of fractures is 1:10 [*Ahlbom, 1991b*] indicating a distance between water conductive fractures of about 4-8 m.

Many studies concerning fractures are found in the literature and this 4th order discontinuity has been studied in more detail than the above mentioned discontinuities. A very important fact that has emerged from experiments in Stripa [*Abelin, 1986, Abelin et al., 1987, Abelin et al., 1990, Birgersson et al., 1992*] and other investigation sites is that the water-transmissive fractures in granitic rock do not act as plane parallel slots, but let water pass through limited parts of the fractures, channels. Although there are exceptions, many channels seem to be localized to where fracture planes intersect.

The hydraulic conductivity in these 4th order discontinuities is estimated to be: 10^{-11} m/s [*Ahlbom, 1991, Pusch et al., 1991*].

Subhorizontal fracture zones

Subhorizontal or gently dipping fracture zones dip 0-30^0 from the horizontal plane and does not intersect the ground surface and are therefore not indicated by lineament analyses or ground geophysical measurements. These zones are mainly interpreted by interpolation of fractured sections found in boreholes. Some of the zones seem to belong to 1st as well as 2nd order discontinuities, but due to lack of data it is difficult to do a more accurate classification of these zones.

The subhorizontal fracture zones have been studied at the investigated sites from boreholes with typical depths of 600-800 m. A compilation of available information indicates on the average one subhorizontal fracture zone from the ground to the bottom of the boreholes. This indicates a spacing of about the same order as the depths of the boreholes, approximately 700 m. It is expected that the frequency of subhorizontal fractures are the same as for the more steeply fracture zones except for the upper 100-150 m of the bedrock where subhorizontal fracture zones are more common.

These subhorizontal fracture zones are estimated to have hydraulic conductivities of 10^{-7} m/s [*Ahlbom, 1991*].

Hydraulic conductivity

Estimates regarding average hydraulic conductivity for different order fracture zones and the surrounding rock mass have been given above and are summarized in Table A6-1. These estimated hydraulic conductivities represent conditions at 500 m depth and are based on hydraulic tests performed within the SKB site investigation program [*Ahlbom, 1991,* *Pusch et al., 1991*]. The given values should, however, be considered as rough estimates since the hydraulic conductivity can vary considerably between different fracture zones as well as within a fracture zone.

Regional fracture zones, 1st order discontinuities: There is a considerable lack of data regarding hydraulic conductivity in these zones. The estimated K-value, $K=10^{-7}$ m/s, is based on investigations in Svartboberget and Singözonen [*Ahlbom, 1991*]. Pusch et al. have estimated the K-value to 10^{-6} m/s for this kind of discontinuity.

Local fracture zones, 2nd order discontinuities: A typical K-value is 10^{-9} m/s based on information from borehole measurements performed for the KBS-3 study. The variation in data is, however, large and the conductivities found at the Finnsjön site are about 10^{-7} m/s. A representative hydraulic conductivity is therefore 10^{-8} m/s. Pusch et al. have estimated the K-value to 10^{-7} m/s for this kind of discontinuity.

Minor intrablock fracture zones, 3rd order discontinuities: An estimated K-value of 10^{-9} m/s is assumed. However, data from Stripa indicates conductivities one to two orders of magnitude higher. Pusch et al. have estimated the K-value to 10^{-8} m/s for this kind of discontinuity.

Subhorizontal fracture zones: The subhorizontal fracture zones observed at the SKB sites have been found to have a hydraulic conductivity 10^{3}-10^{5} times that of the surrounding rock mass. A typical value for these fracture zones is 10^{-7} m/s.

Surrounding rock mass: Based on investigations at the KBS-3 sites, a typical value is 10^{-11} m/s.

Table A6-1. Estimated average hydraulic conductivities at 500 m depth for different orders of fracture zones and the surrounding rock mass.

Discontinuity	Hydraulic conductivity [m/s] Ahlbom/Pusch et al.
Regional fracture zones (1st order)	$10^{-7}/10^{-6}$
Local fracture zones (2nd order)	$10^{-8}/10^{-7}$
Minor intrablock fracture zones (3rd order)	$10^{-9}/10^{-8}$
Fractures (4th order)	$10^{-11}/10^{-11}$
Subhorizontal fracture zone	10^{-7}/-
Surrounding rock mass	10^{-11}/-

Compilation of rock characteristics at 500 m depth

The studies of Ahlbom and Pusch et al. describe the same discontinuities, but end up with different hydraulic conductivities. Table A6-2 gives the characteristics for rock at 500 m depth that are used in this study.

Table A6-2. Rock characteristics at the 500 m level to be used in this study.

Discontinuity	Spacing perpendicular/parallel [m]	Width [m]	Hydraulic conductivity [m/s]
1st order	3200/6900	50-150	10^{-7}
2nd order	400/800	1-20	10^{-8}
3rd order	50-100	0.5-2	10^{-9}
4th order	0.4/0.8	0.01	10^{-11}
Subhorizontal fracture zones	700	*	10^{-7}

*Not possible to assess

1.4.2 Groundwater composition at 500 m level

For the repository concepts that are to be located at about 500 meters depth, the variations that can occur in the water chemistry are mainly site specific. The water composition presented here is therefore representative for all alternatives at the 500 m level. In Table A6–3 the composition of fresh water based on measurements of the water from borehole BFI01 at Finnsjön, and the water composition used in the SKB 91 study are compiled [*Ahlbom and Smellie, 1989*] and [*Bruno and Sellin, 1991*].

Table A6-3. Fresh water composition.

Spec.	Meas. conc. [mg/l]	"SKB91 water" [mg/l]
Ca	76.0	76.0
Na	23.0	23.0
Mg	6.3	6.3
K	3.2	3.2
Fe	9.0	9.0
Si	6.2	6.0
Cl	61.0	61.0
Br	0.3	0.3
F	0.6	0.6
NO_3	0.006	0.5
SO_4	8.3	8.9
HCO_3	220.0	220.0
pH-value	6.9	6.9
Eh-value	+40	-200/650
Depth	71-85	500

The composition of the "SKB91 water" is meant to be used for both oxidizing and reducing condition as can be seen from the two Eh-values of -200 and 650. The concentration of NO_3 is high for the "SKB91 water" but this is of no consequence for the longtime integrity of a repository of either design.

Depending upon the localization of a repository, salt water can be present at the repository level of 500 meters, as is seen in Finnsjön. One such typical water composition of a salt water is given in Table A6-4. Both the measured values from Finnsjön and the "SKB91 water" are included.

Table A6-4. Saline water composition.

Spec.	Meas. conc. [mg/l]	"SKB91 water" [mg/l]
Ca	1600	1600.
Na	1700.	1700.
Mg	120.	120.
K	13.0	13.0
Fe	0.016	0.016
Si	5.4	6.0
Cl	5500.	5500.
Br	29.0	29.0
F	1.2	1.2
NO_3	0	0
SO_4	380.	380.
HCO_3	48.0	48.0
pH-value	7.0	7.0
Eh-value	+400	-200/650
Depth	439-459	500

1.5 Host rock description for VDH

Rock at levels ranging from 2000 to 4000 m is significantly less described in the literature than rock at the 500 m level. The compilation given below is based on the study by Juhlin and Sandstedt [*1989*]. The geological model for Swedish rock at great depths is mainly based on the results from the Gravberg-1 deep borehole within the Siljan Ring area. The most important geological information from the borehole, related to deep borehole storage of spent nuclear waste, is summarized below:

- The rock is highly fractured down to a depth of about 1200 m. Below this depth fracture zones, which typically extend over 2-20 m, occur at a frequency of about every 200-300 m.

- Hydraulic conductivity measurements between 1250 and 3200 m indicate a hydraulic conductivity within the interval $K=10^{-9}$ - 10^{-10} m/s. This conductivity probably corresponds to the most permeable zones in the rock mass.

- Highly saline fluids (salinities of 10-15 %) are present below 6000 m.

- Isotope data on calcite indicate that groundwater may percolate to great depth.

- A temperature gradient of 1.61 °C/100 m was measured after a period of 10 months.

- Data from different sources, including the Gravberg-1 borehole, indicate a stress field where the vertical stress is lithostatic, the minimum horizontal stress is 2/3 of the vertical stress and the maximum horizontal stress is somewhat larger than the vertical stress.

A review of geoscientific data available from other deep boreholes in crystalline rock confirms in principle the geological model based on the Gravberg-1 borehole. The following is proposed for crystalline rock:

- Below 500-200 m the average hydraulic conductivity if the rock is orders of magnitude lower than that of the rock above.

- The deep rock features have likely more or less stagnant fluid systems with higher salinities than the upper part of the bedrock.

Fractures

The Gravberg-1 borehole penetrates numerous fracture zones, which typically extend over 2-20 m of the borehole and occur at a frequency of about every 200-300 m, except in the upper 1200 m of the hole, where they occur at a frequency of about every 50-100 m.

To summarize, the upper 1200 m of borehole in the Gravberg-1 well contains significantly more fracture zones than the borehole below 1200 m. These fracture zones in the upper part of the well are most probably open and able to conduct fluid. The zones that exist below 1200 m may contain open fractures and could also conduct fluids. However, they are not nearly as numerous as above 1200 m. Lack of reliable conductivity tests over the most interesting fracture zones make it difficult to determine the quantity of open fractures at depth in these zones.

Hydraulic properties

Hydraulic measurements in borehole Gravberg-1 have been performed with fairly good accuracy in the interval between 1250 and 3200 m. Below this depth, data are influenced by different mud additives clogging permeable fissures during the pressure test therefore only qualitative data are available below 3200 m, thus only relative values of permeability can be calculated.

The hydraulic conductivity has been tested at depths from 1250 to 3200 m in sections with varying length. The lengths of the tested sections varied between a few tens of meters to about 2000 m. The hydraulic conductivities obtained ranges between 10^{-10} to 10^{-9} m/s. Testing of the interval 5452-6957 m gave an average hydraulic conductivity of $6 \cdot 10^{-12}$ m/s. This section of the borehole was, however, drilled with a high solids content oil-based drilling fluid which may have plugged a majority of the naturally open fractures. Even if plugging has occurred, the results show that very low conductivities surrounding the wellbore are present in this depth range.

In the 12 km deep borehole at the Kola peninsula a fracture zone was found at about 4500 m depth showing that it is possible to have permeable zones at large depths in crystalline rocks. The one in-situ measurement of permeability reported, giving a value of about 10^{-19} m^2 (10^{-12} m/s) at 6370 m, is still relatively high considering the depth of the well.

A compilation of permeability measurements from deep boreholes located in crystalline rocks in USA, Germany, France, Switzerland, United Kingdom, CIS and Sweden, is given in Figure A6-2. Data from these deep boreholes also show that:

- Surface water circulation appears to be dominant down to depths around 1000 m.

- Higher salinity water is mainly found at 1200 to 3500 m depths. One major exception in this compilation is the Gravberg borehole, where saline waters are first found at depths larger than 6000 m.

- The permeability at depths below 1000 m is in the range 10^{-20} to 10^{-15} m^2, with a typical value close to 10^{-17} m^2.

- The temperature gradient varies between 1.3-9 °C/100 m, with a typical value close to 3 °C/100 m.

Compilation of properties at large depths

Based on information from these deep boreholes Juhlin and Sandstedt [*1989*] propose the following model for the behavior of crystalline rock:

The upper 1000 m (this depth can probably vary from 500-2000 m) contains a zone of fractured rock with average permeabilities several orders of magnitude greater than that of the rock below. This zone also has a separate or distinct fluid system with generally lower salinities than the fluid deeper down. Below about 1000 m the rock is much more competent. However, there will exist fracture zones within the competent rock which have considerably higher permeability than the surrounding rock. These fracture zones within the rock may contain different fluid systems that are not in contact with one another or have not been mixed during the time span corresponding to the age of the fluids.

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