Technical Report

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# Project JADE

## Comparison of repository systems

## Executive summary of results

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December 2001

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# Preface

Following the results of several comparisons of the KBS-3 method with other repository methods for geological disposal of spent nuclear fuel, KBS-3 was maintained as the reference method in the SKB programme, which was launched in 1992 and aimed at start of deep disposal in Sweden at the earliest convenience. The field activities are scheduled to progress stepwise, and start with site investigations on more than one site and include continuous evaluations and intercomparison of geoscientific conditions as well as of other technical and socio-economical issues of importance. The information gained during site investigations is also scheduled to be used for site adaptation of repository design and layout, activities that also will progress stepwise with more detailed studies in each step.

A study in 1992 (Project on Alternative Systems Study – PASS) identified several variants of the KBS-3 method as potentially interesting, and the project JADE (Jämförelse Av DEponeringsmetoder, in English: Comparison of disposal methods) was initiated in 1996 with the aim of evaluating if any of these variants should be considered for future studies.

The JADE study has concentrated on more detailed analysis of key technical issues related to KBS-3 variants with horizontal deposition followed by a new comparison between those variants and the reference concept with vertical deposition. The conclusions are that KBS-3 with vertical deposition holes should remain as reference concept, and that deposition in medium long horizontal deposition holes should be studied further with the aim of clarifying the technical feasibility of emplacement and the means of handling water inflow. KBS-3 with horizontal deposition of a single canister in each hole should not be studied further.

The results of JADE are now presented, much later than initially planned, which means that some of the results have already been adopted and applied in SKB's work. This report has due to this a tendency of already being part of the past.

Many experts have been engaged in the project work with Håkan Sandstedt having the head responsibility for arriving at conclusions as well as compilation of this report.

Äspö, December 2001

Christer Svemar

Project Manager

# Abstract

KBS-3 has since 1984 been the reference method for disposal of spent fuel in Sweden. Several other methods like WP-Cave, Very Deep Holes and Very Long Holes have been evaluated and compared with KBS-3. Though the methods have been judged to have a high safety potential, KBS-3 has been shown to provide advantages in the combined judgement of “long-term performance and safety”, “technology” and “costs”.

In the present study, different variants of the KBS-3 method have been analysed and compared with the reference concept KBS-3 V (V for vertical). The variants are: KBS-3 H (H for horizontal) and MLH (medium long holes) – with canisters in a horizontal position, single or in a row respectively. The comparison has been carried out separately for the interim items “technology”, “long-term performance and safety” and “costs” respectively. The outcome in each of these comparisons have finally been combined in a ranking.

This ranking placed KBS-3 V in the top followed by MLH and KBS-3 H. Vertical deposition of a single canister in one deposition hole, KBS-3 V, is robust as gravity is used for lowering the canister and the bentonite into the deposition hole and since each canister has its own barrier in the near field, which reduces the risk for interference between canisters.

The drawback for MLH is the uncertainty about the emplacement technique as well as the impact of weak rock and water leakage into a long deposition hole for several canisters. The advantage is that a smaller volume of rock has to be excavated. This is positive regarding the long-term performance and safety, environmental impact and costs. KBS-3 H does not have the same positive potential.

The conclusion of the JADE study is that KBS-3 V should remain as reference concept, and that MLH should be studied further with the aim of clarifying the technical feasibility of emplacement and the means of handling water inflow. It is recommended that KBS-3 H with deposition of a single canister in each hole should not be studied further.

The JADE-project was initiated in 1996, and the main part of the study was carried out during 1997 and 1998. This report is published in 2001. The JADE study is consequently based on presumptions that were valid a few years ago. Some of these presumptions have been modified since then. The new presumptions are, however, not judged to change the overall conclusions.

# Sammanfattning

KBS-3 har sedan 1984 utgjort referensmetoden för slutförvaring av använt kärnbränsle. Flera andra metoder har utvärderats, såsom WP-Cave, mycket djupa hål – VDH (Very Deep Holes), och mycket långa hål – VLH (Very Long Holes) och jämförts med KBS-3. Även om alla metoderna har bedömts ha en hög potential för god långsiktig säkerhet har KBS-3 visats ha fördelar vid en samlad bedömning av "långsiktig funktion och säkerhet", "teknik" (för byggnation och installation) och "kostnader".

I den föreliggande studien har olika varianter av KBS-3-metoden analyserats och jämförts med referenskonceptet KBS-3 V (V för vertikal). Dessa varianter är: KBS-3 H (H för horisontell) och MLH (medellånga hål) med kapslarna i horisontellt läge, ensamma eller i rad. Jämförelsen har gjorts separat för "långsiktig säkerhet", "teknik" och "kostnader" och sedan sammanfattats i en rangordning.

Denna rangordning placerade KBS-3 V högst upp, MLH därefter och KBS-3 H sist. Vertikal deponering av en kapseln, KBS-3 V, är en robust metod eftersom gravitationen utnyttjas för att föra ner kapsel och bentonit i deponeringshålet, och eftersom varje kapsel har sin egen barriär i närområdet vilket begränsar risken för påverkan emellan kapslarna.

Nackdelen för MLH är osäkerheten med deponeringstekniken samt den påverkan dåligt berg och vatteninflöde till deponeringshålet kan ha på flera intilliggande kapslar. Fördelen är att en mindre bergvolym behöver tas ut. Detta har positiva effekter på förvarets långsiktiga funktion och säkerhet, miljöpåverkan och kostnaden. KBS-3 H har inte samma positiva potential.

Slutsatsen av JADE-studien är att KBS-3 V bibehålls som referenskoncept, och att MLH studeras ytterligare i syfte att klargöra deponeringsteknikens tekniska genomförbarhet liksom sätt att handskas med vatteninflöde till deponeringshålen. Det rekommenderas att KBS-3 H med horisontell deponering av en kapsel per deponeringshål ej studeras vidare.

JADE-projektet påbörjades 1996 och huvuddelen av studien genomfördes under 1997 och 1998. Denna rapport publiceras 2001. JADE studien bygger följaktligen på förutsättningar som gällde för ett antal år sedan. Vissa av dessa har förändrats. De nya förutsättningarna bedöms dock inte påverka de övergipande slutsatserna.

# Contents

# 1 Background

The KBS-3 method, based on deposition of canisters in vertical deposition holes, is since 1984 the reference concept for disposal of Swedish spent nuclear fuel. The repository principle is based on a multi-barrier system in the bedrock at 400-700 metres depth below the ground surface, with the spent fuel encapsulated in copper canisters with a cast iron insert, which are surrounded by a bentonite buffer.

SKB has also developed and evaluated other repository methods. During a period between 1986 and 1989, the WP-Cave method was evaluated and compared with KBS-3. The result of the evaluation showed that WP-Cave was judged to fulfil high demands on long-term performance and safety but that the advantages of KBS-3 outweighed the advantages of WP-Cave.

Three other methods; Very deep holes (VDH), Very long holes (VLH), Medium long holes (MLH) have also been developed and analysed. These were evaluated and compared with KBS-3 in a Project on Alternative Systems Study (PASS) /SKB, 1992/.

The comparisons in the PASS-study included comparisons of “long-term performance and safety”, “technology” and “costs”. All compared methods were judged to fulfil the demands on “long-term performance and safety”. The conclusion was however that KBS-3 and MLH were valued to be the best although the comparison was not completely unambiguous. Concerning the technology, the deposition process in KBS-3 was judged to be more robust concerning the technical feasibility and more flexible. There was a considerable advantage for MLH in the comparison of the costs. In a final judgement, where the advantages in the deposition process in KBS-3 were included, KBS-3 was ranked ahead of MLH.

The possibility in KBS-3 to dispose the canisters in horizontal deposition holes in the walls on both sides of the deposition tunnel has been studied. This variant, KBS-3 H, is judged to be attractive from an economical point of view since the total length of deposition tunnels can be reduced compared to KBS-3 V.

In 1996, SKB initiated project JADE. The aim with the project is to enter more deeply into key issues concerning horizontal deposition. The study comprise a detailed comparison of the alternatives KBS-3 H and MLH with the reference concept KBS-3 V. The study include comparisons of “long-term performance and safety”, “technology” and “costs”. The comparisons regarding “long-term performance and safety” and “technology” are based on bored deposition tunnels. The “costs” have been calculated based on excavated deposition tunnels, which was in accordance with the prerequisite for the PLAN work /SKB, 1997/.

# 2 Objectives

The objective with project JADE is to determine if a horizontal version of the KBS-3 type repository also should be studied further in the future. In this report, the name KBS-3 stands for a repository method featuring a copper canister with a cast iron insert, and surrounded by a bentonite buffer at about 500 m depth in Swedish crystalline bedrock.

The comparison within JADE comprises the following variants of KBS-3:

- KBS-3 with vertical deposition holes (KBS-3 V).
- KBS-3 with horizontal deposition holes (KBS-3 H).
- Medium Long Holes (MLH).

The different variants are illustrated in Figure 2-1. A detailed description is given in Appendix 1.

The comparison is based on the current knowledge of the different repository variants. In order to perform the comparison, it has been necessary to conduct some supplementary studies and to evaluate special issues. Examples are studies of the principles of radiation shielding during the deposition process, studies of procedures and equipment for emplacement of bentonite blocks and deposition of canisters, and a technical up-date of MLH.

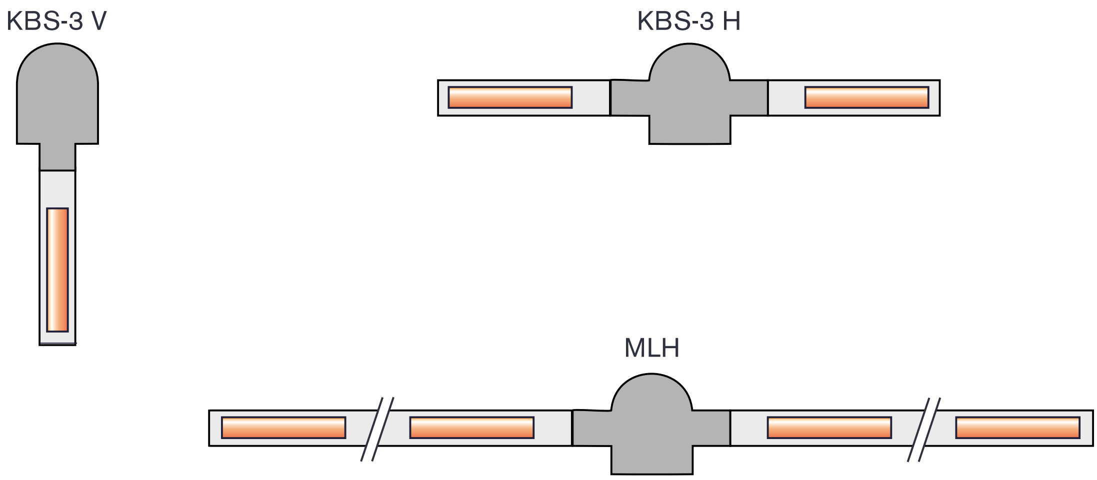



*Figure 2-1 Schematic illustrations of variants of KBS-3 included in the JADE-project.*

# 3 Description of Project JADE

## 3.1 General

The project JADE was conducted according to the flow scheme illustrated in Figure 3-1. The goal was to limit the complexity of the comparison in each step. In this way, the main objective could be fulfilled with reasonable efforts and yet the robustness of the comparison could be maintained.

A general prerequisite was that the comparison should be based on the same type of canister that has been developed for vertical deposition. In KBS-3 V and KBS-3 H it is possible to deposit two canisters in each deposition hole. This has not been addressed in the comparison, but will be investigated later as part of method optimisation.

The following studies have been conducted within project JADE to form the basis for the comparison:

- Update of MLH.
- Geoscientific studies.
- Studies of techniques and equipment for deposition of bentonite blocks and canisters.
- Study on the importance of radiation shielding during deposition.

The study of importance of radiation shielding has been included in the development work of techniques and equipment for handling and deposition of canisters. In addition, an independent expert group (Appendix 2) has evaluated this topic.

The variants KBS-3 H and MLH have been evaluated and compared with the reference concept KBS-3 V. The comparison was in a first stage subdivided into the three interim items:

- Technology.
- Long-term performance and safety.
- Costs.

In a second stage these comparisons were summarised, evaluated and a final comparison and ranking of the KBS-3 variants were performed, see Figure 3-1.

The main results from the JADE study is presented in this report, which is based on the following sub-reports:

- Beskrivning av MLH metoden, SKB R-01-29 (in Swedish) /Sandstedt et al, 2001/.
- Jämförelse av teknik, SKB R-01-30 (in Swedish) /Sandstedt and Munier, 2001/.
- Jämförande kostnadsanalys mellan olika deponeringsmetoder, SKB R-01-31 (in Swedish) /Ageskog, 2001/.
- Geovetenskapliga studier, SKB R-01-32 (in Swedish) /Munier et al, 2001/.

- Process- och maskinbeskrivning av utrustning för deponering av kapslar i horisontella deponeringshål, SKB R-01-33 (in Swedish) /Kalbantner, 2001a/.
- Process- och maskinbeskrivning av utrustning för deponering av kapslar i medellånga deponeringshål, SKB R-01-34 (in Swedish) /Kalbantner, 2001b/.
- Metod- och maskinbeskrivning av utrustning för deponering av kapsel i vertikalt deponeringshål, SKB R-01-35 (in Swedish) /Jansson et al, 2001/.
- Long-term function and safety, Comparison of repository systems, SKB TR-01-18 /Birgersson et al, 2001/.

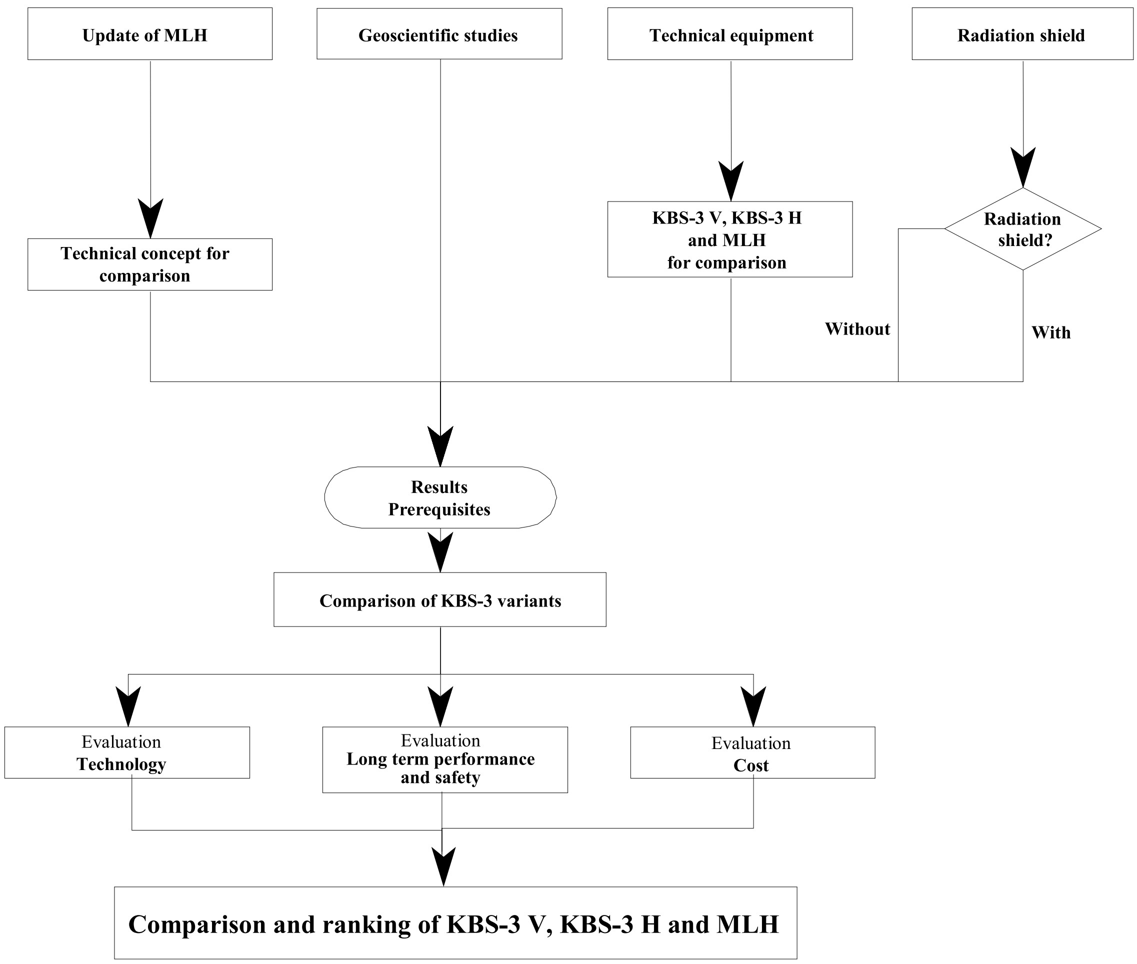



***Figure 3-1*** *Flow scheme illustrating the process applied for comparison and ranking of the studied KBS-3 variants.*

## 3.2 Update of MLH

Recent technical achievements bring both pros and cons to the alternatives studied in PASS in a way that requires analysis. Furthermore, the technical solution of MLH in the PASS comparison was undeveloped, so the first step in JADE was to update previous description of MLH /SKB, 1992/. This updated description of MLH comprises repository layout, construction of the repository, techniques and equipment for deposition of canisters, and emplacement of bentonite blocks /Sandstedt et al, 2001/. The study was conducted in conjunction with ongoing studies of equipment for deposition and current knowledge of boring tunnels with small diameters (1.6-2.4 m) was taken into consideration.

One prerequisite with the update of MLH was to base the concept on blind-boring technique instead of horizontal raise boring, thereby reducing the number and length of tunnels.

## 3.3 Geoscientific studies

In order to compare the KBS-3 variants with regard to “long-term performance and safety” it was considered necessary to analyse differences with respect to the impact of various geoscientific conditions. The objective has been to identify and if possible to quantify these differences. The investigation has been subdivided into separate studies concerning rock mechanics, hydrogeology and structural geology.

The geological conditions used for the comparisons are predominantly based on investigations of the TBM tunnel at the Äspö Hard Rock Laboratory. As a consequence thereof, the results are generally specific to the site but conclusions of general nature have also been possible to make.

## 3.4 Study of techniques and equipment for deposition

To form a basis for updating and comparison of the KBS-3 variants, various prerequisites have been studied. Examples of such studies are:

- whether transportation systems shall be based on rails or wheels,
- how to supply power to the transportation system,
- where transfer to the deposition equipment will be conducted,
- most favourable principle of radiation shielding the canister and
- whether canisters and bentonite should be deposited in one operation or separately.

Studies of techniques and equipment for deposition comprise KBS-3 V, KBS-3 H and MLH.

The process of canister retrieval is not included in the comparison. Retrieval is here defined as the process in which canisters are made free from the bentonite, taken out from the deposition hole and placed in a radiation shield.

## 3.5 Study of radiation shielding

To compare deposition with or without radiation shielding the following studies were conducted:

- Technical evaluation of both alternatives.
- Malfunction analyses.
- Type of radiation shield/container (size and weight).
- Comparison of costs.

The comparison is based on a malfunction analysis, which describes various consequences of accidents, including radiation exposure of personnel. The analysis of radiation shielding comprised both a normal deposition operation and various predicted accident scenarios.

## 3.6 Methodology of comparison and ranking

The comparison of KBS-3 variants is based on a systematic approach where different criteria have been organised in a hierarchic structure. The analysis have been made for the same interim items ("technology", "long-term performance and safety" and "costs") as in PASS /SKB, 1992/ with due considerations to technological development since the PASS project. In addition, new information from SR 97 now exists about important processes for the long-term performance and safety of a repository /Pers et al, 1999/, which provides a basis for a more detailed analysis of differences in "long-term performance and safety".

The ranking of the KBS-3 variants has been performed in two stages. In a first stage, the variants are compared with regard to the three interim items. In a second stage, the ranking of the interim items are weighed into a final ranking.

The extent of the three items is described below:

- "Technology". The scope comprises methods and processes for producing the deep repository with a quality required to achieve the necessary long-term performance and safety.

- "Long-term performance and safety". The scope comprises stipulated requirements and criteria as well as the sensitivity of the performance of the different barriers for existing uncertainties and for various events in the geological environment in the repository after closure.

- "Costs". The scope comprises all aspects and factors that distinguish the KBS-3 variants by the choice of cheaper or more expensive methods and equipment.

The comparison is for the interim items "technology" and "long-term performance and safety" based on weighing of pros and cons for each item in the hierarchy. The comparison of the interim item "costs" is based on cost calculations for the respective variant. The presumptions for the comparison of KBS-3 variants are given in chapter 4.

# 4 Description of the deep repository

## 4.1 General

Several parts of the deep repository will be the same for all three studied variants such as surface facilities, access ramp and shafts, central area, and part of the transport tunnels. The comparison of variants presented in this report with regard to “technology” and “cost” is therefore limited to transport and deposition tunnels and deposition holes.

KBS-3 V is the reference concept in the Swedish programme. A schematic drawing of a deep repository in accordance with KBS-3 V is given in Figure 4-1. The canisters are deposited in holes in the bottom of the deposition tunnels.

KBS-3 H is judged to be economically attractive in comparison with KBS-3 V as the number of deposition tunnels could be reduced. The canisters are deposited in horizontal deposition holes located in the wall of the deposition tunnels.

MLH consists of approximately 250 m long deposition holes, drilled in the walls of a transport tunnel. The canister are deposited after each other in positions separated by compacted bentonite. MLH is also judged to be economically attractive in comparison with KBS-3 V.

The deep repository is planned to be constructed in two stages. The first stage is estimated to accommodate 5-10 % of the total quantity of spent fuel. The second stage includes deposition of the remaining quantity of spent fuel.

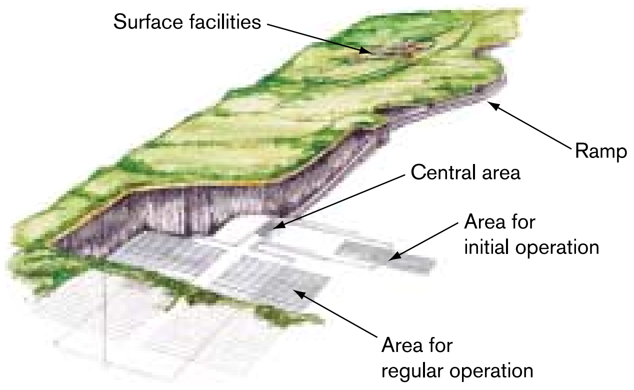



***Figure 4-1*** *Schematic layout of the deep repository with a ramp from the above-ground facilities to the below-ground facilities.*

A schematic illustration of transport tunnels, deposition tunnels and deposition holes is shown in Figure 4-2. Detailed descriptions of the KBS-3 variants are presented in Appendix 1 and technical specifications are found in Appendix 3.

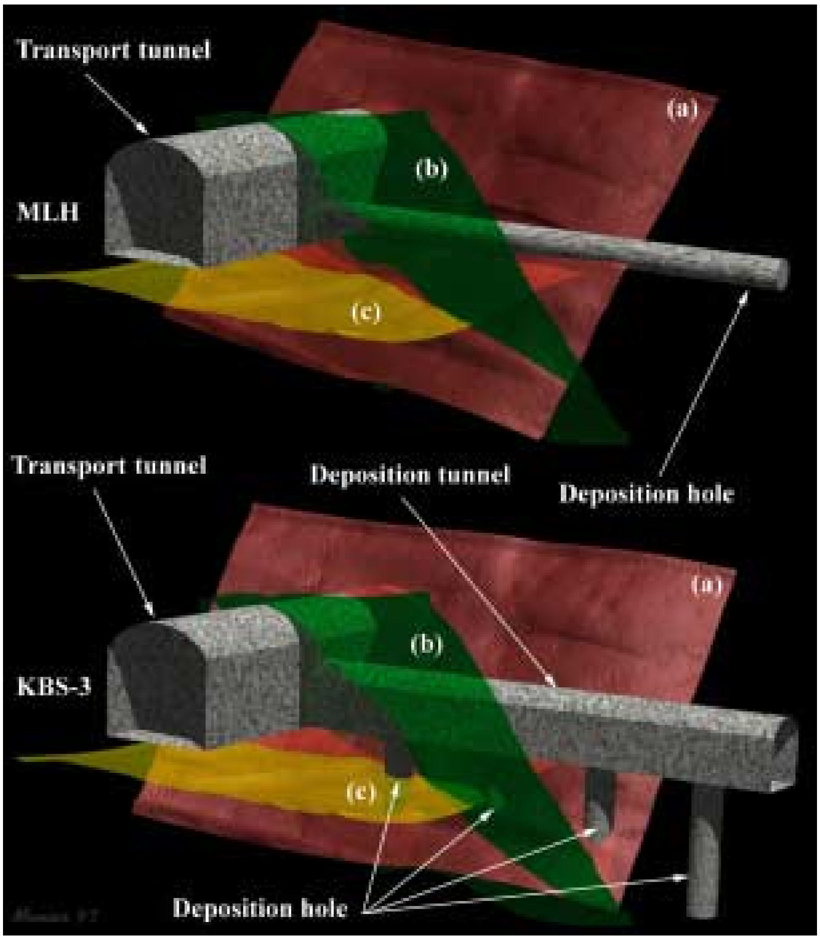



***Figure 4-2*** *MLH and KBS-3 V. Schematic illustration of deposition holes, deposition tunnel and transport tunnel. The figure illustrates the case with blasted deposition tunnels.*

## 4.2 Size of the tunnels

Special equipment will be needed for the emplacement of bentonite blocks and the deposition of canisters. Development of deposition equipment for the three KBS-3 variants has been a part of the project JADE. The development work include several possible techniques and equipment for the different KBS-3 variants. More detailed design work will be needed before it is possible to propose a suitable technique for emplacement of bentonite blocks and deposition of canisters.

The development work include systems with and without radiation shielding during the deposition process. During the progress of the JADE project, SKB made the decision that all handling of the canister should be carried out with a surrounding radiation shielding. This implies that the size of the deposition equipment will be larger and thus, the size of the deposition tunnel must be increased.

The design of the equipment for deposition of canisters will influence the size of the deposition tunnels. This uncertainty is included in the cost comparison, see Chapter 9.

The most plausible technique has been chosen for the comparison of "long-term performance and safety" and "technology".

## 4.3 Spacings of deposition holes and deposition tunnels

The distance between the canisters in the repository is determined by the maximum allowed temperature at the canister surface and in the bentonite. The temperature distribution is influenced by the thermal power generated by the radioactive decay in the spent fuel, the repository layout and material properties for bedrock and bentonite.

The heat distribution around the repositories has been analysed with the finite-element-code ANSYS, version 5.3. The principles for the temperature calculations are presented in PLAN-97 /SKB, 1997/.

The distance between the canisters is defined by the spacing between the deposition tunnels (deposition holes for MLH) and the spacing between the canisters in the deposition tunnel (end to end distance between the canisters for MLH). These two parameters could be chosen in order to minimise the cost of the repository. The calculated spacing between deposition tunnels and canister positions is given in Table 4-1.

**Table 4-1 Spacing/distance between canisters and deposition tunnels.**

| | Canisters | Deposition tunnels |
|---|---|---|
| KBS-3 V | Spacing 6.3 m | Spacing 40 m |
| KBS-3 H | Spacing 7.1 m | Spacing 60 m |
| MLH | Distance 1.2 m | Spacing between deposition holes 40 m |

## 4.4 Canister

In this study, it has been assumed that the canister is designed for 12 BWR (boiling water reactor) assemblies with boxes or 4 PWR (pressurised water reactor) assemblies and that the same canister can be used in all three KBS-3 variants.

The canister is 4.83 m long and has a diameter of 1.05 m. A 50 mm thick copper shell will provide corrosion protection and a cast iron insert will provide mechanical strength. The total weight of the canister loaded with spent fuel will be about 25 tons. The canister is shown in Figure 4-3.

The copper lid is welded on by means of electron or friction stir welding. This weld can only be inspected from the outside and to confirm its tightness is one of the most sensitive activities in the canister sealing process.

The total number of canisters has in this study been assumed to be 3 800 corresponding to 25 years of operation of the Swedish nuclear power plants /SKB, 1997/.

*Figure 4-3 Copper canister with a cast iron insert.*

## 4.5 Bentonite barrier

In all three KBS-3 variants, a bentonite buffer will surround the canister. The emplacement method differs, but a presumption in the study has been that the buffer properties (density, permeability etc) are in principal the same in all KBS-3 variants after closure and saturation. The specification for the buffer is given in Appendix 3. The emplacement methods and the possibility to add bentonite pellets in order to obtain prescribed properties differ between the KBS-3 variants. The risk for and the effects of a buffer that obtain inferior quality are discussed in Chapters 7 and 8.

It has been assumed for all three KBS-3 variants that the canister will be centered in the deposition hole and surrounded by a 0.35 m thick saturated bentonite buffer. This is expected to be obtained by filling the gap between the bentonite and the borehole wall with pellets in KBS-3 V and by using slightly thicker bentonite blocks in KBS-3 H and MLH. It has been assumed that it is not necessary nor feasible to add pellets in horizontal deposition holes.

Although the canister is heavy and has a high density it is assumed for all three KBS-3 variants that the canister will be centered in the deposition hole when the bentonite swells, and will remain centred and not sink through the bentonite.

### 4.5.1 Tunnel backfill

The deposition and transport tunnels have been assumed to be backfilled with a mixture of bentonite and crushed rock. The composition is expected to be 15 weight % bentonite and 85 weight % crushed rock. This will result in higher hydraulic conductivity compared to the buffer in the deposition holes that will consist of 100% bentonite.

The amount of backfill will differ between KBS-3 V/KBS-3 H and MLH. The backfilled volume in KBS-3 V and KBS-3 H is about 700 000 $m^3$ whereas the volume in MLH is less than 200 000 $m^3$, see Figure 4-4. It should be noted that the volume of the backfill in access tunnels and shafts has not been included in the comparison.

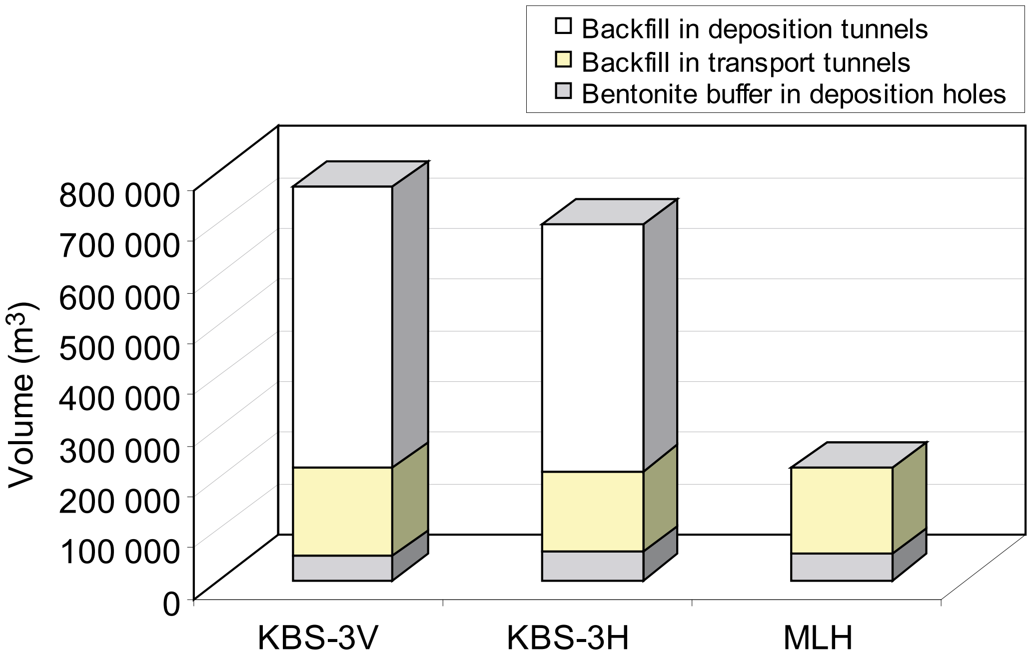



*Figure 4-4* *Volume of tunnel backfill and bentonite buffer in KBS-3 V, KBS-3 H and MLH. Based on deposition of 3 800 canisters.*

### 4.5.2 Construction and stray materials

Construction materials such as cement, concrete and rock bolts will be introduced in the tunnels and in the bedrock surrounding the deposition holes and tunnels in order to stabilise the rock and to reduce the water inflow into the tunnels during the construction and operational phases. Corrosion and degradation of construction materials will result in formation of corrosion/degradation products. Stray materials such as organic materials, oil spill, acids from batteries, nitrogen oxides from blasting etc will be left in the repository.

These chemical species might influence the water chemistry (pH, Eh, concentrations of ions and organics). The organics might form complexes and colloids. These effects could influence the properties of the buffer, backfill and the canisters as well as the radionuclide migration. It is therefore advantageous to reduce the amounts of construction and stray materials. The positive aspects related to construction materials such as reduced water inflow, less degradation of the buffer etc, are mainly restricted to early times.

The average and maximum quantities of construction and stray materials that will remain in the repository with blasted tunnels have been estimated in /Jones et al, 1999/. The quantities correspond to a KBS-3 V repository and are presented in Table 4-2. These amounts could however be reduced by using other types of explosives or boring of deposition tunnels, more careful cleaning of deposition tunnels and holes etc. The amount of construction and stray materials in KBS-3 V/KBS-3 H with bored deposition tunnels and MLH are expected to be smaller compared to the data given in Table 4-2 since no explosives are used and cleaning of bored tunnels or holes is easier than cleaning of blasted tunnels. Furthermore, the amount of stray materials left from transport of excavated rock is reduced in MLH and also in KBS-3 H compared to KBS-3 V since the excavated rock volumes are smaller and less transport of excavated rock will take place.

The total amount of construction and stray materials are judged to be largest in KBS-3 V mainly due to the larger excavated rock volume that will result in more transport of excavated rock. One difference between the three KBS-3 variants is, however, that the major parts of stray materials in KBS-3 V and KBS-3 H will be left in the deposition tunnel whereas the stray materials in MLH will be left in the deposition holes.

**Table 4-2 Average and maximum quantities of construction and stray materials per canister in a KBS-3 V repository with blasted tunnels /Jones et al, 1999/.**

| **Construction and stray material** | **Amount in KBS-3 V [kg/canister]** | |
|---|---|---|
| | Average | Maximum |
| Grouting, cement | 250 | 1 500 |
| Shotcrete, cement | 250 | 1 250 |
| Rock bolts, steel | 70 | 200 |
| Oil products | 2 | 27 |
| Battery acid | 0.01 | 0.3 |
| Rubber from tires | 0.2 | 1 |
| Organic material from human activities | 1 | 21 |
| Other organic material | 0.5 | 2 |

## 4.6 Other presumptions

### 4.6.1 Near-field rock

The hydraulic properties in the near-field rock will have impact on pathways and travel times for escaping radionuclides. The extent and properties of the excavation disturbed zone is important for the hydraulic properties in the near-field rock. The comparison of KBS-3 variants is based on the results from the ZEDEX experiments on disturbed zones, see Figure 4-5.

The rock close to a tunnel or a deposition hole will be disturbed due to the excavation. Several experiments aiming at studying the magnitude and extension of this disturbance have been carried out. One of the more ambitious experiments is the ZEDEX experiment carried out in Äspö HRL /Emsley et al, 1997/.

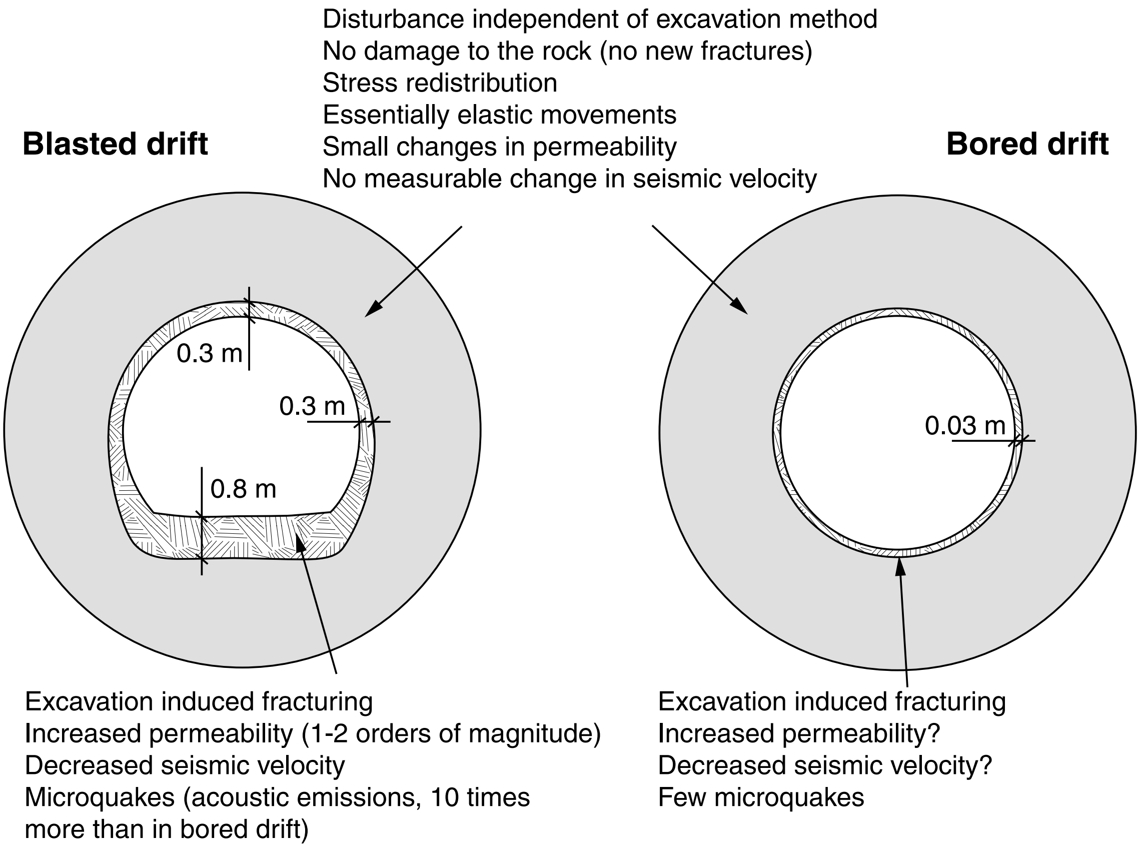



*Figure 4-5    Summary of the results from the ZEDEX experiment.*

It can be seen in Figure 4-5 that the excavation disturbed zone (EDZ), with increased fracturing and increased permeability, is significantly larger around blasted tunnels (0.3-0.8 m) than around bored tunnels (< 0.03 m). Furthermore, a stress redistribution zone will be formed. This zone will extend further out, about three tunnel diameters according to the rule of thumb, and will be independent of excavation method. This zone shows no new fractures and only small changes in permeability, which is expected, since only elastic movements are expected in this zone /Emsley et al, 1997/.

### 4.6.2 Far-field rock

No specific repository site was selected for this study. The repository has been assumed to be located in "typical" Swedish bedrock at a depth of about 500 m.

The far-field rock is defined as the undisturbed bedrock surrounding the repository. The three studied KBS-3 variants will have similar extensions and will therefore be intersected by similar discontinuities.

### 4.6.3 Biosphere

The repository area in all three KBS-3 variants is assumed to be about 2 $km^2$. The compared repositories are located in the same rock volume. The overlying recipients are therefore expected to be the same.

### 4.6.4 Heat generation and temperature increase

Heat will be generated in the canisters due to radioactive decay. This will increase the temperature in the buffer and the tunnel backfill. The temperature in the buffer surrounding the canisters will increase considerably compared to the "normal" temperature at repository depth. The temperature in the buffer will however be below the maximum allowed temperature on the canister surface in all KBS-3 variants.

The temperature increase in the backfill will be quite small for all three KBS-3 variants /SKB, 1997/. The limited temperature increase is not expected to significantly enhance the degradation of the backfill in any of the variants.

# 5 Geoscientific studies

## 5.1 General

The objective with the geoscientific studies performed as a part of the JADE-project has been to evaluate the influence from the rock mass and its discontinuities on KBS-3 V, KBS-3 H and MLH. The basic scope of the studies have mainly been to compare the different deposition concepts with regard to long-term performance and safety, mechanical stability of the repositories and area distribution of the repositories.

The geoscientific studies were subdivided into three separate investigations concerning hydrogeology, rock mechanics and structural geology. The studies are summarized in this chapter and presented in the report:

- Geovetenskapliga studier, SKB R-01-32 /Munier et al, 2001/.

A basic assumption has been that the procedure for accepting canister position is identical for KBS-3 V, KBS-3 H and MLH. From an economical point of view the differences are mainly coupled to the number of rejected canister positions.

The described investigations are mainly based on geological conditions and data from the Äspö HRL. As a consequence thereof, the results presented here are site specific but conclusions of general nature can also be made.

## 5.2 Hydrogeology

Studies concerning the influence on the deposition methods with respect to hydrogeological conditions included an analysis of the hydraulic anisotropy at Äspö HRL. The investigation showed that the transmissivity of the bedrock is influenced by the direction of drilled probe holes and differs between $4 \cdot 10^{-7}$ $m^2/s$ for holes drilled to north west and $2 \cdot 10^{-9}$ $m^2/s$ for holes drilled in a north eastern direction.

The transmissivty data has been used in order to evaluate the number of rejected positions for deposition for different directions of deposition tunnels (KBS-3 V and KBS-3 H) and deposition holes (MLH). This calculation was carried out by the geostatistic code BayMar (Bayesian Markov Geostatistical Model). As the transmissivity differs fairly much depending on the directions also the number of rejected canister position will differ depending on the direction of the deposition tunnels and deposition holes with regard to an assessed inflow criteria.

DFN-modelling (Discrete Fracture Networks) and the FracMan code have been used for evaluation of the number of accepted canister positions. With FracMan and associated codes the number of intersections between fractures has been estimated for deposition holes drilled in vertical or horizontal direction. The number of intersections is a qualitative measure of the transmissivity and inflow of water to a deposition hole. The same result is given as by the BayMar analysis but the difference in rejected canister positions for deposition in different directions is much less pronounced and is judged to be of marginal importance.

MLH is assessed to be more sensitive to water inflow to the long depositions tunnels and thus only recommended for bedrock with low hydraulic conductivity and with low frequency of fractures of types D2 and D3 /SKB, 1999/. As a consequence thereof MLH is considered to be less suitable for rock conditions such as the Äspö HRL rock mass. Further investigations of MLH may revise this statement.

## 5.3 Rock mechanics

The objective with the rock mechanic studies was to compare the effect of deposition of canisters in different directions, i.e. vertical or horizontal as well as parallel or perpendicular towards the main in-situ horizontal stress. The studies also comprised a comparison between blasted and bored deposition tunnels for KBS-3 V and KBS-3 H.

The studies were concentrated to stability analysis of the rock mass close to the deposition holes (near field rock) with regard to in-situ stresses and fracturing of the bedrock. In addition, the studies also comprised an analysis of the rock mechanical influence of the water flow in the near field rock around the deposition holes. The following numerical codes were used; BEASY (a Boundary Element Model), PlastFEM (a Finite Element Model) and 3DEC (a Discrete Element Model).

The rock mechanical analysis showed that KBS-3 V with blasted deposition tunnels and MLH will be the most robust design with respect to the direction and magnitude of the main in-situ stresses. KBS-3 H is sensitive to the direction of the stresses, but will be the best alternative if the deposition tunnels can be oriented parallel to the main horizontal in-situ stress.

As described above, differences in mechanical stability have been identified. However, engineering measures, such as bolting can solve the problems associated with instability of the tunnels. Of more importance are effects that may influence the long-term performance and safety such as movement in fractures and an increase of the conductivity of the near-filed rock.

## 5.4 Structural geology

The geological conditions at Äspö HRL, mainly data from the bored tunnel at a depth of 350 to 450 meters, were used for evaluating the importance of the structural geology. The number of discriminating fractures that could not be accepted to intersect any deposition hole is judged to be less than 5 % of the total number of mapped fractures.

DFN-modelling (Discrete Fracture Networks) and the code FracMan was used for calculation of the number of fractures and the number of intersections between fractures and deposition holes located in different directions. The calculation shows that some differences exist between the KBS-3 variants according to the influence of geological structures and the acceptance of positions for deposition of canisters. Identified differences are, however, minor and thus of little importance for the comparison.

Structures, mainly fault zones and minor fractures with increased hydraulic conductivity, that will influence the acceptance of canister positions do not exist to such extent in Äspö HRL that it will influence the comparison.

## 5.5 Geological investigations

No differences were identified between the KBS-3 variants with respect to geological pre-investigations from ground surface. With a given investigation effort, the information density is judged to be essentially identical.

Geological investigations at repository level are similar for the different variants. However, the prerequisites for JADE prevent extensive drilling in the vicinity of deposition holes, which is a disadvantage for MLH. Yet, the deposition holes in MLH are topologically identical to their equivalents in KBS-3V/KBS-3 H, which consequently implies that drilling nevertheless could be accepted in MLH. In the authors' opinion, the differences regarding geological pre-investigations are insignificant.

# 6 Technique and equipment for deposition

## 6.1 General

As a basis for comparison of KBS-3 variants it is necessary to evaluate and suggest suitable deposition techniques and equipment for deposition. The selection of deposition technique will influence the size of the deposition tunnels, and thus the cost for the repository.

SKB have studied different techniques for deposition of canisters and emplacement of bentonite for a long period of time. In the JADE study, the development work has been focused on alternatives for vertical and horizontal deposition of a single canister (KBS-3 V and KBS-3 H) and serial positioning in horizontal deposition holes (MLH). The studies are summarized in this chapter and presented in the reports:

- Process- och maskinbeskrivning av utrustning för deponering av kapslar i horisontella deponeringshål, SKB R-01-33 /Kalbantner, 2001a/.
- Process- och maskinbeskrivning av utrustning för deponering av kapslar i medellånga deponeringshål, SKB R-01-34 /Kalbantner, 2001b/.
- Metod- och maskinbeskrivning av utrustning för deponering av kapsel i vertikalt deponeringshål, SKB R-01-35 /Jansson et al, 2001/.

At the start of project JADE the suggested deposition techniques were based on a technical system without a surrounding radiation shielding in the deposition tunnels. However, at a later stage a study within JADE was initiated to compare deposition techniques with and without radiation shield surrounding the canister in the deposition tunnel.

As a part of project JADE an expert group (Appendix 2) was formed to support SKB with viewpoints and advice about the development of techniques and equipment for deposition of canisters. This expert group consisted of representatives with experience from SKB's facilities, the mining industry and scientific R&D work. One advice put forward by the group was that the deposition of canister should be carried out with surrounding radiation shielding. Furthermore, the opinion of the group was that it should be possible to develop a deposition technique that fulfils high demands of quality and safety in the deposition process for all studied KBS-3 variants.

## 6.2 Radiation shielding

A malfunction analysis has been performed in order to evaluate the need for radiation shielding during the whole deposition process. The analysis was qualitative and comprised the part of the deposition process that is performed in the transportation and deposition tunnels. The analyses of vertical (KBS-3 V) and horizontal deposition (KBS-3 H and MLH) were performed independently as a part of the development work for deposition techniques and equipment.

In the malfunction analysis, the deposition process was subdivided into a number of well-defined activities in which malfunction may occur that hinders the deposition process. The cause of malfunctions could vary considerably ranging from malfunction of a single component to malfunction of a complete system. Depending on whether the canister is enclosed in a radiation shield or not, different measures are taken.

The performed malfunction analysis show that it will be complicated to carry out repair works if the canister is handled without a surrounding radiation shielding.

The radiation shield will consist of a cylinder of steel and plastic. For deposition of a whole package, canister and bentonite, the bentonite will also add to the radiation protection. The weight and size of the deposition equipment will increase with radiation shielding and larger deposition tunnels are needed.

The cost for deposition with an enclosing radiation shield is judged to be about 100 MSEK higher as compared to deposition without shielding (January 1997 cost level) due to the need for larger deposition tunnels. The cost difference is estimated as a “present value” with an interest rate of 4 %. The cost for predicted malfunctions is included in the estimate.

## 6.3 Deposition equipment for KBS-3 V

The development work comprises 11 different technical alternatives for deposition of canisters in vertical deposition holes. The different alternatives are presented in Figure 6-1. All studied alternatives are judged feasible to be developed into deposition equipment that fulfils stated requirements. In order to reduce the space in the tunnel, alternatives with deposition of canister and bentonite buffer in separate operations are favoured.

Based on established requirements and performed malfunction analysis, the flexibility and complexity in the deposition process and the cost for large deposition tunnels, it is recommended that deposition is carried out by one of the following alternatives.

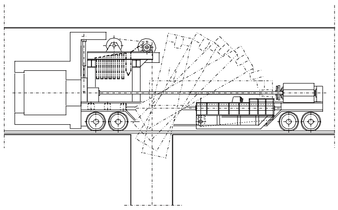
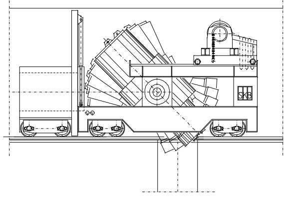
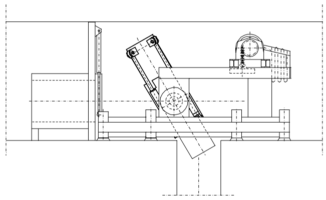
- The canister is transported in a horizontal position and rotated down into the deposition hole using a Cardano movement that utilises the upper part of the deposition hole for rotation. The radiation shield could be opened in the bottom or in the middle of the cask.

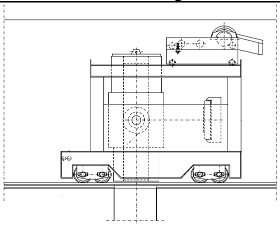
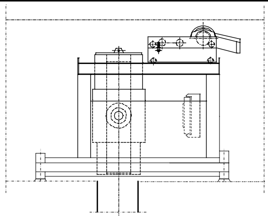
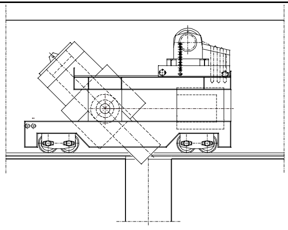
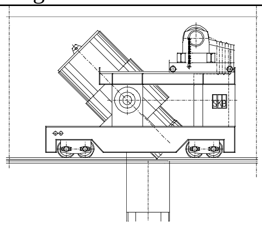
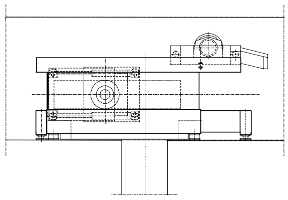
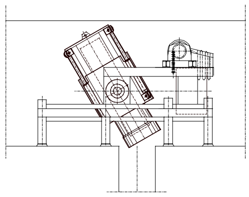
- The canister is transported in a vertical position and is lowered down into the deposition hole. A radiation shield during the deposition process encloses the canister.

The technical principle with transportation and deposition of the canister in vertical position during all steeps in the deposition process is fairly simple compared to alternatives with horizontal transportation and a Cardano movement during deposition. However, due to the required size of the deposition tunnel and thereby the cost of the repository, it is recommended that the deposition of canisters is carried out by a Cardano movement.

More development work is, however, needed to form a basis for a final decision of deposition technique. Alternative V6 has been chosen for comparison of KBS-3 variants (“technology” and “costs”). To have room for the suggested deposition equipment, the deposition tunnel must have a minimum width of 4.2 m and a minimum height of 5.0 m.

A more detailed description of the deposition technique, alternative V6, is presented in Appendix 1.

| Deposition vehicle with an unshielded canister behind a radiation shield | | |
|---|---|---|
| <br>V1: Deposition vehicle with an unshielded canister behind a radiation shield. | <br>V2: Deposition vehicle with canister/bentonite package behind a radiation shield. | <br>V3: Deposition stand with an unshielded canister behind a radiation shield. |

| Deposition vehicle with lying canister in a whole or devisable radiation shield | | |
|---|---|---|
| <br>V4: Deposition vehicle with an enclosing radiation shield. | <br>V5: Deposition stand with an enclosing radiation shield. | <br>V6: Deposition vehicle with a devisable radiation shield. |
| <br>V7: Deposition vehicle for a canister/bentonite package with a devisable radiation shield. | <br>V8: Deposition stand with a devisable radiation shield. | <br>V9: Deposition stand for a canister/bentonite package with a devisable radiation shield. |

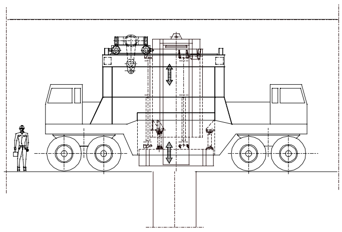
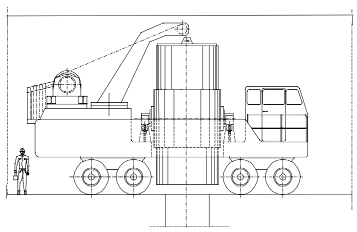
| Deposition vehicle for standing canisters with enclosing radiation shielding | | |
|---|---|---|
| <br>V10: Deposition vehicle with an enclosing radiation shield. | <br>V11: Deposition vehicle for canister/bentonite packages with enclosing radiation shield. | |

***Figure 6-1*** *Studied alternatives for vertical deposition (KBS-3 V). Alternative V6 has been chosen for comparison of KBS-3 variants.*

## 6.4 Deposition equipment for KBS-3 H

The performed development work comprises 16 different technical alternatives for deposition of canisters in horizontal deposition holes, see Figure 6-2. Some alternatives are, however, fairly similar and differ only in details. The grouping of alternatives is based on the following:

- In alternatives H1 to H10 the deposition of canister and emplacement of bentonite blocks are carried out in separate operations.

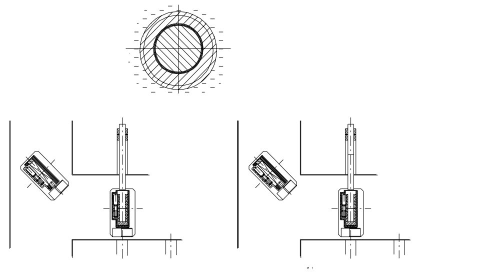
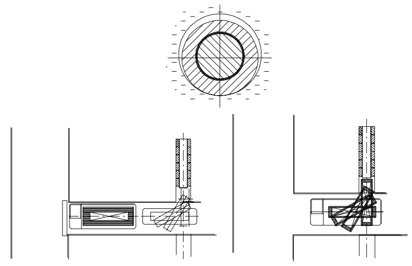
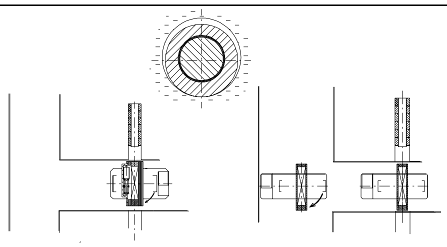
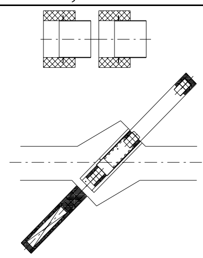
- In alternatives H11 to H16 the deposition of canister and emplacement of bentonite blocks are carried out in one operation (package of a canister surrounded by bentonite blocks).

Alternatives H11 to H14 are based on a novel technology with the package of canister and bentonite placed in a specially designed metallic sleeve resting on roller bearings. During deposition the sleeve is pushed into the deposition hole. When the sleeve is in its correct position the sleeve is rotated and the package of canister and bentonite is rolled off and placed in the bottom of the deposition hole.

Compared to the deposition technique for KBS-3 V, the studied deposition alternatives for horizontal deposition are all based on a more novel technology.

The 16 different technical alternatives have been compared. It has so far not been possible to recommend a suitable deposition technique for KBS-3 H based on current knowledge. However, alternative H6 has been chosen as deposition technique for comparison of KBS-3 variants (“technology” and “costs”). To allow room for the deposition equipment, the deposition tunnels must have a minimum width of 6.2 m and a minimum height of 3.5 m. To ensure tunnel stability and for practical reasons the height of the deposition tunnels should be increased to about 5 m.

A more detailed description of the deposition technique H6 is presented in Appendix 1.

| Deposition in parts with guiding pipe | |
|---|---|
|  H1 H2 |  H3 H4 |
| H1 and H2: Shielded canister in parts with guiding pipe and two vehicles (H2: devisable guiding pipe). | H3: Unshielded canister in parts with guiding pipe and three vehicles, Cardano movement. Alternative H4: Shielded canister, otherwise like H3. |
|  H5 H6 |  H7 |
| H5 and H6: Shielded canister in parts with guiding pipe ant three vehicles. Mounting movement in deposition hole (H5) or in transport tunnel (H6). | H7: Shielded canister in parts with abandoned guiding pipe and three vehicles. Oblique deposition holes. |

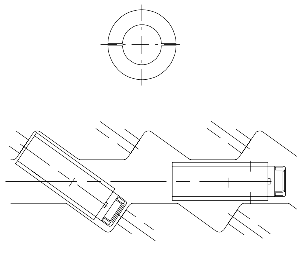
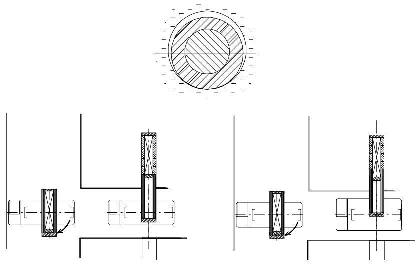
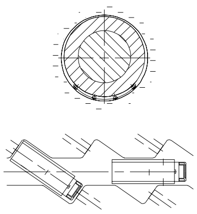
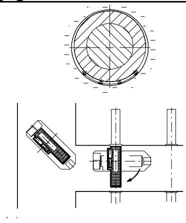
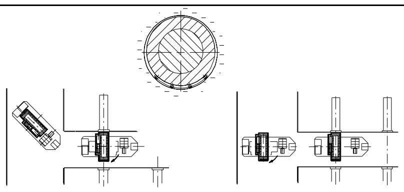
| Deposition in parts, other methods | |
|---|---|
|  H8 |  H9 H10 |
| H8: Non-shielded canister in parts with three vehicles. Split bentonite rings, oblique deposition holes. | H9 and H10: Shielded canister in parts with two vehicles. Shielding pipe with plunge. Mounting movement in transport tunnel (canister partially outside the radiation shield in the deposition hole in alternative H10). |

***Figure 6-2*** *Studied alternatives for horizontal deposition of a single canister (KBS-3 H). Alternative H6 has been chosen for comparison of KBS-3 variants.*

| **Deposition in packages with loading pipe** | |
|---|---|
| <br>H11<br><br>H11: Enclosed shielding of a canister/bentonite package with loading pipe, oblique deposition holes. | <br>H12<br><br>H12: Enclosed shielding of a canister/bentonite package with loading pipe. Mounting movement at deposition hole. |
| <br>H13 H14<br><br>H13 and H14: Radiation shielded canister in two packages with loading pipe and one vehicle. Mounting movement at deposition hole (H13) or in the transport tunnel (H14). | |

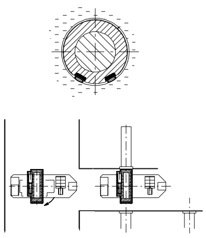
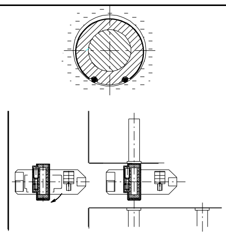
| **Deposition in packages, other methods** | |
|---|---|
| <br>H15<br><br>H15: Enclosed radiation shielding of a single package. Forklift vehicle with caterpillar tracks. | <br>H16<br><br>H16: Enclosed radiation shielding of a single package. Transportation on guiding rods. |

***Figure 6-2*** *continuation.*

## 6.5 Deposition equipment for MLH

The performed development work comprises 12 different technical alternatives for deposition of canisters in long horizontal deposition holes, see Figure 6-3. Some alternatives are fairly similar and differ only in detail. The grouping of alternatives is based on the following:

- In alternatives MLH1 and MLH2 the deposition of canister and emplacement of bentonite is carried out in separate operations.

- In alternatives MLH3, MLH4 and MLH5 the canister and bentonite is deposed in a package in one operation with a loading sleeve.

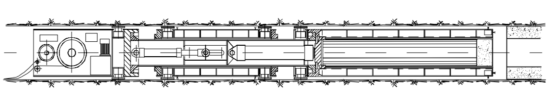
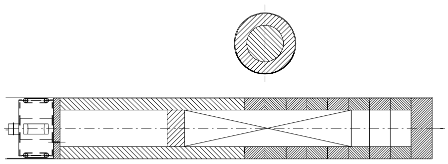
- In alternatives MLH6, MLH7 and MLH8 the canister and bentonite is deposed in a package in one operation with grooves in the buffer.

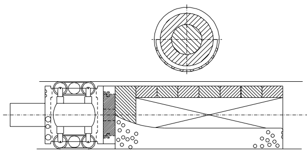
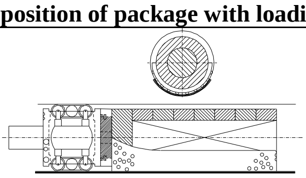
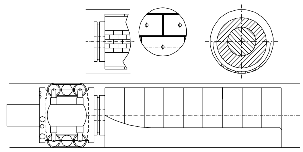
- In alternatives MLH9, MLH10, MLH11 and MLH12 the canister and bentonite is deposed in a package in one operation with a loading pipe.

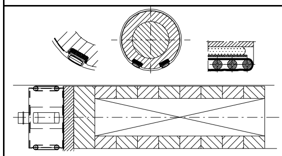
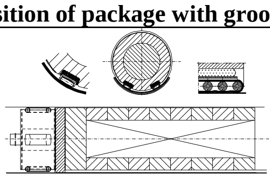
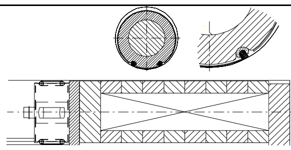
Alternatives MLH3-5 are based on the same novel technology as proposed for KBS-3 H with the package of canister and bentonite placed in a specially designed rotating sleeve resting on roller bearings.

Alternative MLH9 has been further studied with respect to the principle of pushing the package of bentonite and canister forward in the deposition hole. The “pushing “ mechanism is fairly similar to the jacking system used by a tunnel boring machine.

The 12 different technical alternatives have been compared. It has so far not been possible to recommend a suitable deposition technique for KBS-3 H based on current knowledge. However, alternative MLH9 has been chosen as deposition technique for comparison of KBS-3 variants (“technology” and “costs”). The deposition technique and prerequisites for the design of the deposition equipment are presented in Appendix 1.

| Deposition in parts | |
|---|---|
|  |  |
| MLH1: Deposition of partly radiation shielded canister with abandoned guiding pipe. | MLH2: Deposition of partly radiation shielded canister. The canister glides on the bentonite at the end of deposition process. Radiation shield with plunge. |

| Deposition of package with loading sleeve | | |
|---|---|---|
|  |  |  |
| MLH3: Deposition of radiation shielded package lying on a rotating loading sleeve resting on roller bearings. | MLH4: Deposition of radiation shielded package with pivotal loading sleeve on gangway in the deposition hole. | MLH5: Deposition of radiation shielded package lying on an air-cushion, pivotable loading sleeve. |

| Deposition of package with grooves in the buffer | | |
|---|---|---|
|  |  |  |
| MLH6: Deposition of radiation shielded package. Forklift vehicle with caterpillar tracks. | MLH7: Deposition of radiation shielded package. Forklift vehicle with caterpillar tracks resting on a gangway. | MLH8: Deposition of radiation shielded package on sliding rods. |

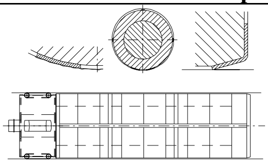
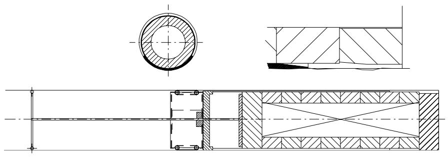
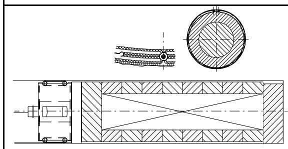
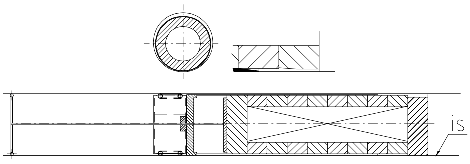
| Deposition of packages with loading pipe | |
|---|---|
|  |  |
| MLH9: Deposition of radiation shielded package within a copper net that glides on the bottom of the deposition hole. | MLH10: Deposition of radiation shielded package with withdrawable, stiff deposition pipe gliding on gangway. |
|  |  |
| MLH11: Deposition of radiation shielded package with withdrawable, flexible deposition pipe gliding on gangway. | MLH12: Deposition of radiation shielded package with withdrawable, stiff deposition pipe gliding on ice. |

***Figure 6-3*** *Studied alternatives for deposition of canisters in Medium Long Holes (MLH). Alternative MLH9 has been chosen for the comparison of KBS-3 variants.*

# 7 Comparison and ranking with respect to technology

## 7.1 General

The comparison and ranking of the KBS-3 variants with respect to “technology” is reduced to a comparison of deposition tunnels, deposition holes and the deposition process and associated processes. Other parts of the repository such as ramp down to the repository, shafts, central area and transport tunnels are essentially similar for the KBS-3 variants and will not influence the ranking.

The comparison and ranking with respect to “technology” is summarized in this chapter and presented in the report:

- Jämförelse av teknik, SKB R-01-30 /Sandstedt and Munier, 2001/.

All criteria that will influence the comparison with respect to “technology” have been structured in a hierarchic order, see Figure 7-1.

Comparison of repository concepts could be performed by several methods. In PASS /SKB, 1992/, the comparison with respect to “technology” was carried out in two phases. In a first phase, the comparison was carried out as a qualitative comparison of criteria. As the criteria have different significance in the comparison, it was concluded that it was not possible to make a final, objective judgement of the best concept with respect to “technology”. The comparison was therefore carried out in a second phase using a panel of six experts /SKB, 1992/. Compared to phase one, the comparison was carried out on the basis of the same hierarchic structure but with the support of the so-called “Analytical Hierarchy Process”, which is based on pair-wise comparison of different criteria. This method yields the relative importance of each criterion versus the overall objective, the best technical solution.

Based on the experience from PASS, and the knowledge of pros and cons of the KBS-3 variants, it was decided that it was not necessary to use the Analytical Hierarchy Process for the comparison within the JADE-project. Instead, the comparison was based on a qualitative comparison of criteria, including the following steps:

1. Description of all criteria that influence the comparison.

2. Identification of criteria of significant importance in the ranking.

3. Comparison.

4. Evaluation of the ranking result including assessment of the need for technical development for the KBS-3 variants.

## 7.2 Criteria for comparison

The hierarchic structure for comparison presented in /SKB, 1992/ is established in three levels, see Figure 7-1.

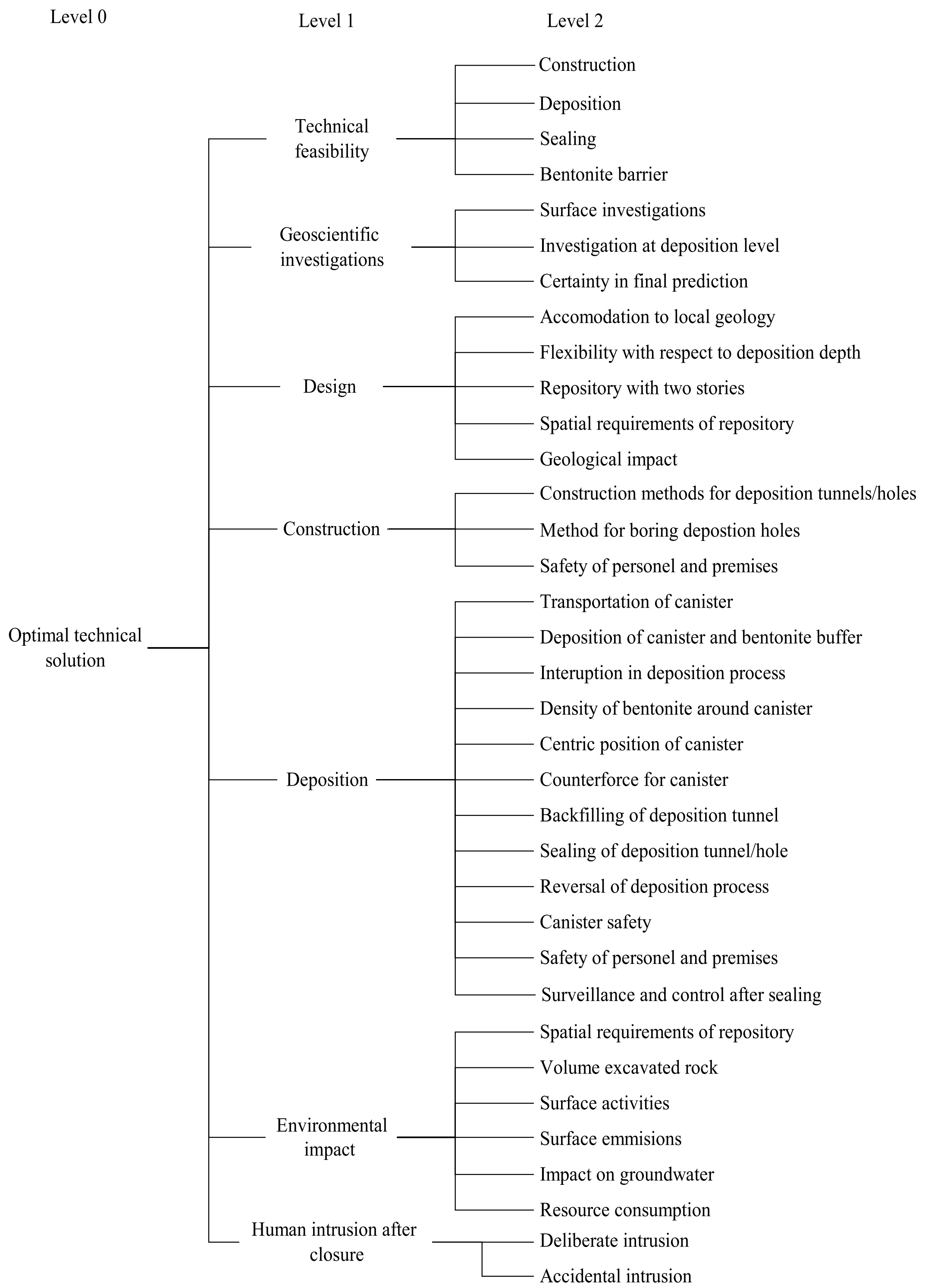



*Figure 7-1 Hierarchic structure for ranking of KBS-3 variants with respect to "technology".*

## 7.3 Comparison and evaluation

### 7.3.1 Criteria and evaluation

#### *Technical feasibility*

One prerequisite for the comparison is that the compared KBS-3 variants are technically feasible with respect to construction, deposition of canisters and closure after deposition. The possibility to achieve required quality of the bentonite barrier is evaluated separately as this criterion has a large influence on the long-term performance and safety. Differences exist between the variants as they are to a variable extent based on proven, fairly proven and unproven technology respectively.

KBS-3 V, which constitutes reference concept in the Swedish programme, is predominantly based on proven construction principles and technology. Yet, there are uncertainties concerning the deposition of canisters and bentonite, the pressing of bentonite blocks, the properties of the bentonite barrier after deposition of canisters and the technique for backfilling the deposition tunnels. To clarify uncertainties and to optimise various repository elements, full-scale tests are currently being performed in the Äspö HRL.

KBS-3 H implies that the deposition holes are drilled horizontally in the walls of the deposition tunnels. For construction of the repository, the same methods will be applicable as for KBS-3 V. The main difference is the orientation of the deposition holes. Horizontal emplacement demands equipment that pushes or lifts the canisters and bentonite blocks into their horizontal position. Conceptual studies have shown that full-scale tests are necessary for the development of adequate equipment and deposition technique.

The deposition tunnels and deposition holes in KBS-3 V and KBS-3 H are replaced with long, horizontal deposition holes in MLH. Existing equipment for boring such holes have to be modified and developed with respect to the straightness of the holes and procedures of fast movements of the equipment between deposition holes. It is, however, judged possible to manufacture or adapt such equipment that fulfils these special requirements. The proposed technique and equipment for deposition of canisters and bentonite need to be further developed and evaluated in full-scale tests. Further, special equipment has to be developed for grouting and rock support works in the small and long holes.

It is considered possible to handle the described uncertainties concerning construction of deposition tunnels, boring of deposition holes and deposition of canisters and emplacement of bentonite by technical improvement. A difference with present design is that the bentonite barrier might achieve a slightly lower density and thereby a higher hydraulic conductivity after homogenisation for horizontal emplacement of canisters.

Based on present know how and that KBS-3 V has been studied more thoroughly and full-scale test are currently been performed, KBS-3 V is ranked higher than the other two variants.

### *Geoscientific investigations*

The comparison of geoscientific investigations involves investigations from surface and on the repository level. The confidence in the final geological prediction is the most important issue to evaluate. The criteria involve analysis of the possibilities to perform necessary investigations and predictions due to repository layout.

No significant differences were identified between the KBS-3 variants with respect to geoscientific pre-investigations from the surface. With a given investigation effort, the information density is judged to be essentially identical for all methods.

Geoscientific investigations at repository level are similar for the different variants. However, the prerequisites for JADE prevent extensive drilling in the vicinity of deposition holes, which is a disadvantage for MLH. Yet, the deposition holes in MLH are topologically identical to their equivalents in KBS-3 V and KBS-3 H, which consequently implies that drilling nevertheless could be accepted in MLH.

In the authors' opinion, the identified differences between the KBS-3 variants regarding geoscientific investigations are insignificant.

### *Design*

The comparison with respect to design covers the possibility to adapt the repository layout to existing geological conditions at the chosen site, flexibility according to repository level, repository constructed on two levels (parted approximately 100 m), extension of the repository and the influence of the repository due to variations in the geological conditions.

The differences that exist regarding geological investigations at repository level are judged to marginally affect the design of the tunnel systems.

Due to similarities in repository layout, the prerequisites for design are in principal the same for the three KBS-3 variants.

### *Construction*

The comparison with respect to construction is restricted to construction of deposition tunnels and deposition holes. The comparison also involves safety for personnel and the function of the repository.

Based on known and proved technology, the methods used to excavate tunnels and to drill deposition holes are similar for KBS-3 V, KBS-3 H and MLH. Therefore, there are no differences between the variants concerning construction technique and safety for personnel and the repository.

Available boring equipment has to be modified with respect to straightness of the holes and speed of re-positioning to new boring positions to fulfil demands for MLH. Conventional techniques for grouting and reinforcement can be used, but special mobile platforms and equipment must be developed for the use in long tunnels of a small diameter (1.75 m). Based on current knowledge it is judged technically feasible to conduct grouting and reinforcement with maintained level of safety for personnel and facilities and still maintain a high quality of performance.

The task of constructing a MLH repository, boring of deposition holes and perform various tasks inside the deposition holes can, with current knowledge, be carried out maintaining the high demands for safety for personnel and the repository facility.

Rock support, i.e. grouting, rock bolts and shotcrete, that is needed in the deposition tunnels for KBS-3 V and KBS-3 H will to some extent also be needed in the deposition holes for MLH. The plugs of compacted bentonite that will be used in MLH for sealing-of discontinuities in close vicinity of the canister do not exist for KBS-3 V or KBS-3 H. Instead, such deposition holes are not used for deposition of canisters. To evaluate the requirements for such plugs, further R&D work is needed with respect to e.g. length of plugs, design and bentonite quality.

Based on current knowledge, MLH must be ranked lower than KBS-3 V with regard to construction. It could also be stated, based on this comparison, that moderate R&D work is judged needed to develop MLH to the same technical maturity as KBS-3 V.

### *Deposition*

The criterion on deposition involves all activities from transportation of the canister down to the repository level, deposition of the canister, emplacement of bentonite barrier and backfilling of the deposition tunnels with a mixture of bentonite and crushed rock. The criterion also include safety for the canister and personnel as well as supervision and control after closure of the repository.

Conceptual studies have been performed in order to outline suitable methods for deposition of canisters and emplacement of bentonite. The methods for KBS-3 V are considered most mature and a full-scale test has been performed at the Äspö HRL. A clear advantage with KBS-3 V is that gravity is used for lowering the canister and the bentonite into the deposition hole.

Several techniques have been proposed for horizontal emplacement according to MLH and KBS-3 H, but extensive investigations and evaluations are necessary before it is possible to recommend a technique for further development. For deposition according to MLH, it has been proposed that bentonite and canisters should be emplaced simultaneously in one package. The technique, for deposition of single packages that are pushed along the floor of the deposition holes, has several advantages including simpler handling with less movements and built-in protection for canister and bentonite.

In KBS-3 V, the gap between bentonite and the wall (approx. 50 mm) of the deposition holes is planned to be filled with pellets of bentonite to ensure that the barrier will obtain desired density and hydraulic conductivity after swelling and homogenisation. To provide for a high thermal conductivity from start, the remaining voids are filled with water after canister deposition. During homogenisation, the bentonite will exert a swelling pressure that is proportional to the density of the bentonite. This will ensure centricity of the canister within the deposition hole providing that the pellets-filling in the gap is fairly evenly thick all around the canister.

During horizontal deposition, the bentonite and canisters are emplaced on the floor of the deposition hole. If bentonite pellets are placed in the gap on top of the canister and bentonite, the canister will be forced down towards the floor of the deposition hole during swelling of the bentonite and will thereby obtain an eccentric position. To avoid eccentric positioning of the canister, it is presumed that filling with pellets will not be performed. Thereby the barrier will, for horizontal deposition, obtain a slightly lower density and accordingly a higher hydraulic conductivity than is the case for vertical deposition.

In MLH, the packages bentonite/canister will be emplaced serially after each other in about 250 m long deposition holes. Inflow of water will accumulate and flow along the floor of the deposition holes towards the transport tunnel. It is not known to what extent such inflow can be tolerated with respect to degradation of the bentonite barrier. It is further possible that water inflow could cause the deposition holes to be sequentially sealed of by the swelling bentonite.

Deposition in individual holes, i.e. KBS-3 V and KBS-3 H, ensures that each deposition is an isolated process, which is favourable from a quality and safety point of view. Further, quality control and surveillance is facilitated due to the possibility of visual inspection.

An eventual continuation of the refinement of deposition techniques covering horizontal emplacement must include detailed investigations on the bentonite barrier. The studies should include the thickness of the barrier, i.e. diameter of the deposition hole, quality of the bentonite, the technique for emplacement of bentonite and canister and the influence and handling of water inflow.

MLH lacks deposition tunnels that must be backfilled with bentonite and crushed rock, which is an obvious difference compared to KBS-3 V and KBS-3 H. The backfilling material is expensive and the technique for backfilling is rather complicated.

The bentonite barrier might with the present design yield a higher density and thus a lower hydraulic conductivity for vertical deposition. Therefore, KBS-3 V is ranked higher regarding “deposition” than the two variants with horizontal deposition.

### *Environmental impact*

The environmental impact analysed in the comparison involves activities during construction and operation of the repository. Issues concerning release of radionuclides are discussed in the comparison with respect to “long-term performance and safety”. The compared criteria are the extension of the repository, volume of excavated rock, construction activities and emissions at surface (noise, exhaust fumes etc), influence on the groundwater in the repository area, and the use of non-renewable resources.

Radiological issues apart, the environmental impact due to the construction of the repository is basically proportional to the volume of excavated rock. Excavated rock is to be transported to surface. The transports cause emission of exhaust fumes and noise, waste water must be purified, etc.

Due to the lesser amount of excavated rock, a MLH repository will have less environmental impact than a KBS-3 V or KBS-3 H repository. However, the volumes of excavated rock are fairly small when compared to the volumes generated by other major underground projects such as mines and traffic tunnels (e.g. The Southern Link, Stockholm) and will be excavated during a long period of time.

#### *Human intrusion after closure*

Human intrusion can be subdivided into deliberate intrusion and accidental intrusion. For instance, deliberate intrusion could occur with the objective to physically damage parts of the repository. Accidental intrusion could occur if boreholes are drilled into the repository during for example mineral exploration.

Since the layouts are basically identical for the three KBS-3 variants, the risk associated with deliberate or accidental human intrusion is equal.

### 7.3.2 Summary of comparison with respect to technology, hierarchy level 2

The comparison of repositories with respect to “technology” on hierarchy level 2 as discussed in section 7.3.1 is summarised in Table 7-1. The comparison is presented as pros “+”, cons “-“ or equal “=” compared to the reference concept KBS-3 V. The comment “not relevant” implies that comparison is not possible due to large differences between the variants.

**Table 7-1 Comparison of KBS-3 variants with respect to "technology". Hierarchy level 2.**

| Criteria<br>Hierarchy level 1 | Criteria<br>Hierarchy level 2 | KBS-3 H | MLH |
|---|---|---|---|
| **Technical feasibility** | Construction | = | = |
| | Deposition, closure | - | - |
| | Bentonite barrier | - | - |
| **Geoscientific investigations** | Surface investigations | = | = |
| | Investigations below ground | = | (-) |
| | Certainty in predictions | = | = |
| **Design** | Adjustment to existing geological conditions | = | (-) |
| | Flexibility with respect to repository level | = | = |
| | Repository constructed in two levels | = | = |
| | Area extension of the repository | = | = |
| | Influence due to variations in the geological conditions. | = | (-) |
| **Construction** | Boring of deposition holes | = | - |
| | Construction of deposition tunnels | = | not relevant |
| | Safety for personnel and repository | = | = |
| **Deposition** | Transport of canister | = | = |
| | Deposition of canister and emplacement of bentonite | - | - |
| | Break in the deposition process | = | = |
| | Density of the bentonite buffer | - | - |
| | Centric position of the canister | = | = |
| | Counterforce for the canister | = | + |
| | Back filling of the deposition tunnel | = | not relevant |
| | Closure of deposition tunnel/deposition hole | = | + |
| | Reverse operation | = | = |
| | Safety for the canister | = | = |
| | Safety for personnel and the repository | = | = |
| | Probation and control after closure | = | (-) |
| **Environmental impact** | Spatial requirements of the repository | = | + |
| | Volume excavated rock | = | + |
| | Surface activities | = | + |
| | Surface emissions | = | + |
| | Influence on groundwater | = | + |
| | Resource consumption | = | + |
| **Human intrusion after closure** | Deliberate | = | = |
| | Accidental | = | = |

### 7.3.3 Comparison and ranking with respect to best repository technology

The comparison with respect to best repository technology, see Table 7-2, shows that no benefits have been identified for KBS-3 H as compared to KBS-3 V. Specially proposed techniques for deposition of canisters and emplacement of the bentonite are, for KBS-3 H, based on a more novel technology. Identified difficulties in the procedure for emplacement of the bentonite blocks indicate that there exists a risk with KBS-3 H of arriving at a too low density in the bentonite buffer, which might influence the long-term performance and safety.

A comparison between KBS-3 V and MLH is fairly complex. The variants differs and so far MLH has been studied more briefly than KBS-3 V. A disadvantage for MLH, as compared to KBS-3 V, is that the proposed technique for deposition of canisters and emplacement of bentonite are based on a more novel and untested technology.

One obvious advantage with MLH, as compared to KBS-3 V and KBS-3 H, is that the excavated volumes are less. This will influence, among other factors, the environmental impact during construction and operation.

A final comparison with respect to "technology" is summarised in Table 7-2. The comparison is presented as pros (+), cons (-) or equality (=) as compared to the reference concept KBS-3 V.

**Table 7-2 Comparison of KBS-3 variants with respect to best technology.**

| Criteria for comparison | KBS-3 H | MLH |
|---|---|---|
| Technical feasibility | - | - |
| Geoscientific investigations | = | = |
| Design | = | = |
| Construction | = | - |
| Deposition | - | - |
| Environmental impact | = | + |
| Human intrusion after closure | = | = |

Based on information about the deposition techniques at their current state of development, KBS-3V is considered to be the best technical solution, followed by KBS-3 H and finally MLH. It should be noted that the proposed techniques have been evaluated by a group of independent experts, see Appendix 2. The opinion of the group is that it should be possible to develop a deposition technique that fulfils high demands on quality and safety in the deposition process for all the studied KBS-3 variants.

# 8 Comparison and ranking with respect to long-term performance and safety

## 8.1 General

The purpose with the work described in this chapter has been to identify and rank differences between the three KBS-3 variants that can be of importance for the long-term performance and safety.

The study has focused on the expected behaviour of the repositories. This implies deposition of intact canisters, slow degradation of the canister and other barriers. In addition, deposition of canisters with an initial defect has been considered. Differences between the KBS-3 variants with regard to scenarios such as glaciation, earthquakes and human activities are briefly discussed.

The comparison and ranking with respect to “long-term performance and safety” is summarized in this chapter and presented in the report:

- Long-term function and safety, Comparison of repository systems. SKB TR-01-18, /Birgersson et al, 2001/.

## 8.2 Identification and ranking of differences

The “long-term performance and safety” have been ranked based on prevailing geological and hydrological conditions at an assumed repository site in typical Swedish bedrock.

The ranking has not been based on a safety analysis, but on qualified judgements carried out in a stepwise manner. Even though the ranking has been based on qualified judgements, the judgements are to some extent subjective. A comparison based on safety analysis may therefore lead to partly other conclusions than those presented below.

### 8.2.1 Methodology

Differences in the expected function of the KBS-3 variants that may influence the “long-term performance and safety” have been identified. The identification of the differences has been based on the interaction matrices developed for the KBS-3 V repository concept during the SR 97 safety study /Pers et al, 1999/. Within the SR 97 study, all interactions were classified based on their importance for the “long-term performance and safety”. The following classes were used:

- Important interaction that should be part of a safety analyses.
- Interaction with limited or uncertain influence.
- Interaction with negligible influence.

The important interactions in the interaction matrices for the near-field /Pers et al, 1999/, the buffer /Pers et al, 1999/, and the far-field /Pers et al, 1999; Skagius et al, 1995/ have been considered in this study. The KBS-3 variants have been ranked based on differences related to the important interactions.

### 8.2.2 Ranking

The KBS-3 variants have been ranked with regard to:

- Long-term repository performance.
- Radionuclide migration from a degraded canister.
- Radionuclide migration from a canister with an initial damage.

The long-term performance represents the estimated possibility for the KBS-3 variant to maintain the function of the canister, bentonite buffer and tunnel backfill in a long-term perspective.

The radionuclide migration from a degraded canister will depend on the properties of the surrounding barriers at the time for the radionuclide release. The canister is designed to maintain its function during at least 100 000 years.

Ranking has also been performed for radionuclide migration from a canister with an initial damage. At this time, the properties of the other barriers are expected to be in accordance with the design criteria.

#### *The ranking procedure*

The ranking has been carried out for the identified differences between the KBS-3 variants. The ranking is presented in two steps:

1. Comparison with respect to function of each barrier (Section 8.3).

2. Identification of differences that are of such importance for the “long-term performance and safety” that they influence the ranking (Section 8.4).

## 8.3 Function of each barrier

The major differences between the KBS-3 variants are described below. Descriptions are given for each barrier, starting with the canister. A concluding remark has been included for each barrier. Qualified judgements were used in order to find out if a barrier could be expected to have a better function in any of the variants. These judgements have been compiled in Table 8-1. The integrated rating for each barrier is based on a qualified, weighted compilation of all identified differences.

### 8.3.1 Canister

#### *Deposition of canister with an initial defect*

One or a few of the deposited canisters might have an initial defect that has not been observed during the quality controls. Such a defect is most probably found in the weld around the lid, which is made after fuel emplacement and can consequently only be inspected from the outside. Any defect is assumed to be restricted to having an area of a few $mm^2$.

Radionuclides may be released from this defect in the canister by diffusion, by advection, or with water displaced by gas. The position of the defect will influence the release of radionuclides. The most unfavourable location is in the lowest part of the canister as positioned in the deposition hole. The reason is that this would allow the total amount of water inside the canister to be expelled by gas. In this respect, the vertical position of the canister in the deposition hole as in KBS-3 V will be more favourable than the horizontal position in KBS-3 H and MLH. The weld at the lid in a KBS-3 V canister will always be located in the highest positioned part of the canister while this weld will be partly located in the lowest part in a horizontal canister. Figure 8-1 illustrates possible positions of an initial defect in the canister lid weld.

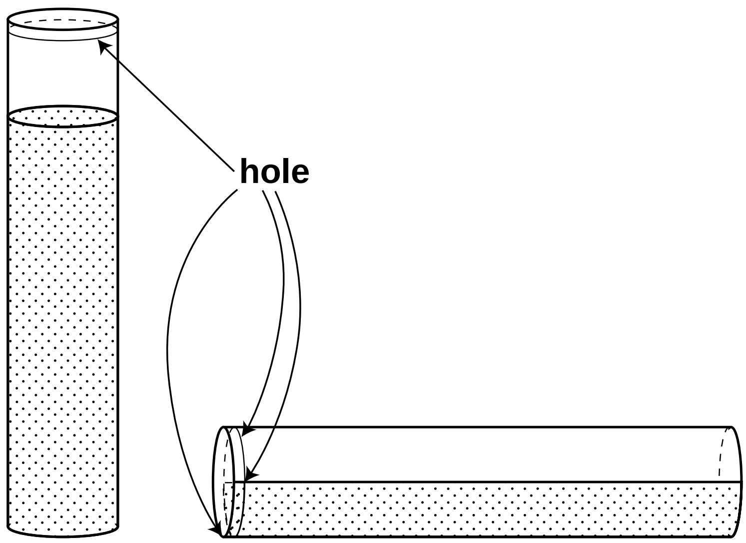



*Figure 8-1 Possible positions of an initial defect in the canister.*

The cast iron insert in the canister has conservatively been neglected as barrier for the radionuclide migration.

### *Position of initially intact welds*

All welds might be initially intact, but the welds are still expected to constitute the part of the canister where corrosion is most likely to occur. The most unfavourable location of a defect is still in the lowest part of the canister.

### *Surface area within the canister available for reactions*

Water penetrating a defect canister may initiate a number of reactions e.g. fuel alteration, fuel dissolution/precipitation, radiolysis, sorption/desorption, instant release of soluble elements in gaps and cracks, and corrosion of metals (copper, steel and zircaloy). These processes depend, at least to some extent, on the contact surface area between the penetrated water and the reacting material. A horizontal position of the canister will result in larger contact surfaces until the canister is half-filled with water. Production of gases due to corrosion will probably lead to that the canister will mainly be less than half-filled with water, which implies that a vertical position of the canister (KBS-3 V) is preferable.

### *Heat conduction*

Air trapped in the gap between the canister and bentonite will reduce the heat transfer somewhat. This might increase the temperature inside the canister and thereby lead to increased canister surface temperatures. Consequently, there will be a risk that bentonite in contact with these canister surfaces may obtain a too high temperature which might result in degraded bentonite. A vertical canister is preferential since the air filled gaps can easily be artificially filled with water in the course of deposition. This will reduce the risk for limited heat conduction.

### *Canister - main differences*

The main difference between the KBS-3 variants is related to the radionuclide migration from an initially damaged canister. In this aspect, a vertical canister is to be preferred.

## 8.3.2 Buffer

### *Emplacement of bentonite blocks*

The short as well as the long-term properties of the bentonite buffer is dependent on the emplacement of the bentonite blocks. It is probably considerably harder to avoid that some of the buffer will be flushed out from a horizontal deposition hole (KBS-3 H and MLH) compared to vertical deposition holes (KBS-3 V). This would decrease the buffer density and thereby deteriorate the buffer properties such as the hydraulic conductivity. This problem will probably be smaller for KBS-3 H than for MLH due to the shorter deposition holes. It should be noted that this is a technical problem that probably could be solved.

### *Construction and stray materials*

A fundamental difference is that people will work more in the MLH deposition holes during construction and that transportation will take place in these holes. This will put demands on more grouting and rock bolts in and in the vicinity of the MLH deposition holes. The difference between KBS-3 V and KBS-3 H is not expected to be large, with the exception that a horizontal deposition hole (KBS-3 H) will be easier to keep clean from stray materials.

### *Biological activity*

Biological activity will take place in the deposition holes. This process will start as soon as the holes are drilled and will continue as long as the environmental conditions are suitable. The extent of the biological activity will depend on the time the hole will be kept open, the amount of water that will emerge into the hole, the extent of different human activities in the holes etc. It is advantageous to keep the holes open for as short time as possible and to avoid human activities in the holes. The extent of human activities will be largest in MLH.

### *Water uptake in the buffer*

The water uptake in the bentonite buffer will probably be very uneven during the saturation phase since the emerging water will mainly originate from a small number of water conductive fractures. This uneven uptake of water in the buffer can result in sheer stresses that might affect the integrity of the canister. Uneven swelling is however not expected to cause damage to the canisters in any of the KBS-3 variants.

The magnitude of the forces that might be introduced by the buffer is well above the forces introduced by the weight of the canister. This implies that there is no significant difference between a canister deposited horizontally or vertically if the geometric pattern of the intersecting water conductive fractures is the same.

### *Filling the deposition holes with water*

Uneven stresses on the canister and uneven heat conduction between the canister and bentonite buffer should be avoided if possible. One way could be to fill the deposition holes with water before backfilling of the tunnel in order to have a controlled saturation of the buffer. It is easier to add water to a vertical hole. The differences between the variants are mainly restricted to early times.

### *Adding pellets*

Adding bentonite pellets to the deposition hole will increase the buffer density and thereby improve buffer properties such as the hydraulic conductivity. It is possible to add bentonite pellets to a vertical deposition hole. Pellets can not easily be added to horizontal deposition holes. However, this is compensated by the fact that more compacted bentonite can be used due to available tolerances.

### *Buffer – main differences*

The main difference between the KBS-3 variants is related to the emplacement of the compacted bentonite blocks and the subsequent risk for flushing in horizontal deposition holes, which might result in a reduced density of the bentonite buffer. A reduced density of the bentonite will influence the long-term properties of the repository as well as the radionuclide migration.

Furthermore, it is probably easier to avoid that large quantities of bentonite are flushed out in KBS-3 H compared to MLH.

Another negative effect for MLH is the larger amounts of construction and stray materials in the deposition holes compared to KBS-3 V and KBS-3 H.

These differences between the KBS-3 variants are possible to affect by technical measures.

### 8.3.3 Backfill

### *Backfilled volume*

The volume of backfilled tunnels in the deposition area will differ significantly between the KBS-3 variants. The volume is smallest in MLH. The volume of KBS-3 H is slightly smaller compared to KBS-3 V. A larger backfilled volume is a general drawback from different points of view. This is further discussed below.

### *Backfill properties*

The properties of the tunnel backfill will influence the repository performance and the radionuclide migration, in a short-term as well as in a long-term perspective. Tunnels with backfill may constitute flow-paths for escaping radionuclides if the backfill settle with time, the backfill is degraded or if the design criteria cannot be achieved. It is therefore an advantage to have few and short tunnels that preferably also should be located far away from the canisters. A possible positive effect of backfill is that it has a large surface area that is available for sorption of radionuclides.

All canisters deposited in accordance with KBS-3 V or KBS-3 H will be located just a few meters from the backfilled deposition tunnels. The canisters deposited in MLH will, in average, be located in the order of one hundred meter from the backfilled tunnels. The properties of the backfill in the tunnels will therefore have larger impact on the bentonite properties close to the canisters in KBS-3 V/KBS-3 H compared to MLH. Unexpected events such as rapid degradation of the bentonite in the deposition tunnels, rock movements, and backfill settlement will therefore have larger impact on KBS-3 V/KBS-3 H.

### *Water flow through the backfill*

The degradation of the backfill will depend on the water flow through the backfill, which is dependent on the hydraulic properties in the near-field rock. An important factor for the water flow through the backfill is the extension and the hydraulic properties of the EDZ. The extension of the EDZ around bored tunnels has been assumed to be 0.03 m for all KBS-3 variants. Degradation of the backfill may also occur due to chemical interactions between the bentonite and the crushed rock. The degradation of the backfill due to water flow in EDZ and chemical interactions is expected to be the same for all variants. However, the average distance between backfill and canister is shorter in KBS-3 V/KBS-3 H.

### *Deposition hole – tunnel interface*

The interface between deposition hole and tunnel may constitute a weak part since highly compacted bentonite will be in contact with backfill that has a lower density and higher conductivity. These inferior properties in the tunnel backfill might to some extent influence the properties of the bentonite in the deposition hole. It is therefore an advantage if the canister is deposited far away from the tunnel backfill. Each canister deposited in KBS-3 V/KBS-3 H will be located fairly close to the backfill, whereas, the canisters in MLH will be deposited far away from the tunnel backfill.

The density of the backfill in the deposition tunnel will be largest in the bottom of the tunnel. The deposition holes in KBS-3 V will therefore be in contact with backfill having a high density and the deposition holes in KBS-3 H will be in contact with backfill having lower density. KBS-3 V will probably be preferential even though the swelling forces from the bentonite buffer partly has to be taken up by the low-density backfill at the ceiling of the deposition tunnel straight above the deposition hole.

The weakest section, considering the rock mechanic situation, is probably at the interface between the deposition tunnel and the deposition hole. It can not be ruled out that the rock will break after repository closure due to rock movements caused by heat generation from the canisters or swelling of the bentonite. These rock blocks might influence the properties of the bentonite in the deposition hole. The number of deposition holes, and thereby the risk for rock slabs, is significantly larger in KBS-3 V and KBS-3 H compared to MLH.

### *Construction and stray materials*

Construction and stray materials in the tunnels may affect both the short- and long-term properties of the backfill. In a short-term perspective, construction and stray materials may influence the water chemistry in the backfill, e.g. pH, complexing agents, organic compounds. This could have negative effects on the radionuclide migration. In a long-term perspective, construction and stray materials may influence the hydraulic properties of the backfill.

Fairly large amounts of stray and construction material will remain in the tunnels in all three KBS-3 variants. The distance from a canister to the transport tunnel in MLH is, however, significantly larger compared to the distance from a canister to the deposition tunnel in KBS-3 V and KBS-3 H, which means that the potential impact of stray and construction materials in the tunnels on the long-term performance and safety is significantly smaller.

#### *Biological activity*

Biological activities in the tunnels may have negative effects on both the short- and the long-term performance of the repository. The amount of biological activity per unit exposed area in the tunnel is expected to be about the same for all three KBS-3 variants. The difference in biological activity is related to significantly smaller excavated volumes (and hence less exposed area) in MLH and somewhat smaller volumes in KBS-3 H, as compared to KBS-3 V.

#### *Backfill - main differences*

Tunnels with backfill may constitute flow paths for escaping radionuclides if the backfill is degraded or if the design criteria cannot be achieved.

The main differences between the KBS-3 variants are related to the excavated rock volume, the canister - tunnel distance and the number of tunnel - deposition hole interfaces. A considerable larger rock volume will be excavated in KBS-3 V and KBS-3 H, especially the KBS-3V, compared to MLH. The average distance between canister and tunnel is significantly larger in MLH compared to KBS-3 V and KBS-3 H. The number of intersections between deposition holes and tunnels are significantly lower for MLH compared to KBS-3 V and KBS-3 H.

### 8.3.4 Near-field rock

No important differences with regard to the near-field rock properties have been identified between the KBS-3 variants. This is mainly dependent on the results from the ZEDEX experiment, which indicate that the EDZ has a small extension and is of minor hydraulic importance for bored tunnels.

Other experiments indicate that the extension and the hydraulic conductivity in the EDZ around tunnels may be larger than assumed. If this is the case, then MLH is preferential compared to KBS-3 V and KBS-3 H since the EDZ could constitute an important pathway for radionuclides.

### 8.3.5 Far-field rock

The larger excavated volumes in KBS-3 V/KBS-3 H will give more knowledge regarding the host rock compared to the small excavated volume in MLH. The additional information is however judged to be of minor importance for the knowledge of the site. The knowledge about the host rock in MLH could be increased by additional geophysical measurements or by drilling a few vertical boreholes and by a suitable characterisation programme.

The total volume of excavated rock differs between KBS-3 V, KBS-3 H and MLH. A larger excavated rock volume will increase the water flow in the far-field rock if and when the hydraulic properties in the backfilled tunnels are inferior compared to the surrounding rock. A larger excavated volume (KBS-3 V and KBS-3 H) may therefore induce faster radionuclide migration in the far-field rock.

### 8.3.6 Compilation of differences

The identified differences between the KBS-3 variants for each barrier are discussed in previous sections. To get an overview, the differences are compiled in this section. The function of each barrier in KBS-3 H and MLH has been compared with the function of that barrier in the reference concept KBS-3 V, see Table 8-1.

**Table 8-1 Function of each barrier. Comparison to KBS-3 V. The used notation is: "+" better than KBS-3 V, "-" worse than KBS-3 V, "=" no difference compared to KBS-3 V, "NA" not applicable. "( )" indicate a small difference.**

| Barrier | Long-term performance, engineered barriers | | Radionuclide migration, degraded canister | | Radionuclide migration, early release | |
|---|---|---|---|---|---|---|
| | KBS-3 H | MLH | KBS-3 H | MLH | KBS-3 H | MLH |
| Canister | (-) | (-) | (-) | (-) | - | - |
| Buffer | (-) | - | (-) | - | (-) | - |
| Backfill | = | + | = | + | = | (+) |
| Near-field rock | NA | NA | = | = | = | = |
| Far-field rock | NA | NA | = | (+) | = | = |

It can be seen in Table 8-1 that MLH has advantages as well as disadvantages as compared to the reference concept, KBS-3 V. KBS-3 H do not have any advantages as compared to KBS-3 V.

Some of these differences can be reduced or even eliminated by technical measures. The importance of the differences for the ranking of the KBS-3 variants is discussed in Section 8.4.

## 8.4 Ranking of KBS-3 variants with respect to long-term performance and safety

The differences that are compiled in Table 8-1 are a mixture of minor and major differences between the KBS-3 variants. These differences have been further compiled in Table 8-2, which illustrate differences that are of such importance for the long-term performance and safety that they have a major influence in the ranking. The ranking is mainly based on the expected performance of the repository, which implies release from a degraded canister. Early release from a canister has as well been considered in the ranking, but has been given low priority since the number of deposited canisters having an initial damage is expected to be very low and since the barrier properties are expected to be in accordance with the design criteria at the time for the release.

**Table 8-2 Differences of such importance for the long-term repository performance and safety that they have a major influence in the ranking. Comparison with KBS-3 V. The used notations are: "+" better than KBS-3 V, " –" worse than KBS-3 V, "=" no difference compared to KBS-3 V. "( )" indicate a small difference.**

| **Barrier** | **Long-term performance and safety** | |
|---|---|---|
| | KBS-3 H | MLH |
| Canister | = | = |
| Buffer | (-) | - |
| Backfill | = | + |
| Near-field rock | = | = |
| Far-field rock | = | (+) |

### *Canister*

No major differences related to the canister have been identified that determine the ranking of KBS-3 variants with respect to the long-term repository performance and radionuclide migration.

The identified differences related to radionuclide migration from an initially damaged canister are not judged to be of such importance that they influence the ranking.

### *Buffer*

Horizontal emplacement of the buffer (KBS-3 H and MLH) could result in less favourable buffer density, uneven swelling etc. These problems are possibly larger for long deposition holes, i.e. MLH. Development of proper techniques may eliminate this difference between the KBS-3 variants.

It is foreseen that the amount of construction and stray materials will be larger in the MLH deposition holes compared to the KBS-3 deposition holes. This can be unfavourable for the long-term properties of the buffer and the canister.

### *Backfill*

Tunnels with backfill may constitute flow paths for escaping radionuclides if the backfill properties are degraded or if the design criteria cannot be achieved. The tunnel volume that will be backfilled is significantly smaller in MLH compared to KBS-3 V and KBS-3 H. The distance between a canister and the tunnel is, on average, significantly longer in MLH compared to KBS-3. These differences between the variants are dependent on the different layouts and are hence not possible to influence.

Construction and stray materials as well as the occurrence of biological activity in the tunnels can affect the short-term as well as the long-term properties of the backfill. The amount of construction and stray materials as well as the biological activity can to some extent be adjusted by technical measures.

### *Near-field and far-field rock*

The larger excavated volumes in KBS-3V and KBS-3 H may enhance the radionuclide migration if and when the hydraulic properties in the backfilled deposition tunnels are inferior compared to the surrounding rock.

No other important difference related to the near-field and far-field rock has been identified with respect to the long-term repository performance and safety.

The EDZ might have a larger extension and higher hydraulic conductivity than assumed based on results from the ZEDEX experiments. This would be a disadvantage for all three KBS-3 variants, especially KBS-3 V and KBS-3 H.

### *Other scenarios*

The ranking between the KBS-3 variants has been focused on the expected behaviour of the repository barriers.

Scenarios related to glaciation, seismic events and human activities could influence the repository performance and radionuclide migration. The main differences between the KBS-3 variants with respect to these scenarios are related to the volume of excavated rock and the repository layouts. The amount of excavated rock will be considerably larger in KBS-3 V and KBS-3 H compared to MLH.

The deposition layout will be quite different in the KBS-3 variants. The canisters will be more or less individually deposited in KBS-3 V and KBS-3 H, while MLH is based on disposing a large number of canisters after each other in one deposition hole.

The overall conclusion is that an external disturbance that will affect the repository performance is less probable in MLH due to the smaller excavated rock volume, but might have larger impact since several canisters are deposited in each deposition hole.

## 8.5 Conclusions regarding long-term performance and safety

A comparison of KBS-3 V, KBS-3 H and MLH has been carried out with regard to:

- Long-term performance.
- Radionuclide migration from a degraded canister.
- Radionuclide migration from a canister with an initial damage.

Several differences have been identified. The differences are mainly related to the:

- distance between canister and backfilled tunnels,
- excavated rock volumes and
- deposition hole direction.

Some of these differences are possible to influence by technical measures.

The overall conclusion is that the differences are in general quite small with regard to "long-term performance and safety". None of the differences are of such importance that they discriminate any of the KBS-3 variants.

MLH has the potential to be very robust, especially in a long-term perspective. However, MLH will require research, development, and analysis before it will be established on the same technical confidence level as the reference concept, KBS-3 V.

The difference between KBS-3 V and KBS-3 H is small. The main advantages with KBS-3 H are related to the smaller excavated volume. The main disadvantages are related to the horizontal emplacement of the bentonite buffer and the horizontal canister position. Based on this study, there are no reasons related to the "long-term performance and safety" to abandon KBS-3V for KBS-3H.

# 9 Comparison and ranking with respect to costs

## 9.1 Principle for cost calculation

The cost estimates for the different KBS-3 variants are carried out according to “the Successive Principle”. A description of adjustment of the cost calculation for a deep repository is presented in the PLAN 97 report /SKB, 1997/. The Successive Principle is described in Appendix 4.

Besides the methodology, also technical and cost data have been derived from the PLAN works, mostly from the report PLAN 97, which was forwarded to the authorities in June 1997. Hence, presented cost data refers to price level of January 1997.

The comparison and ranking with respect to “costs” is summarized in this chapter and presented in the report:

- Jämförande kostnadsanalys mellan olika deponeringsmetoder, SKB R-01-31 /Ageskog, 2001/.

In project JADE, the cost calculations are restricted to analysis of the cost difference between the studied KBS-3 variants. The cost difference is generally small compared to the total cost. KBS-3 V constitutes the reference concept in the comparison of the costs.

## 9.2 Calculations of costs

To form a basis for a choice of KBS-3 variant the cost calculations have been performed for four alternatives for KBS-3 V (V1 to V4), four alternatives for KBS-3 H (H1 to H4) and two alternatives for MLH (M1 and M2).

The main difference between the alternatives is the size of deposition tunnels. For MLH, the difference between the two alternatives is the length of deposition holes that is not suitable for deposition of canisters. Those sections will be plugged using compacted bentonite. The result of the calculations is shown in Figure 9-1.

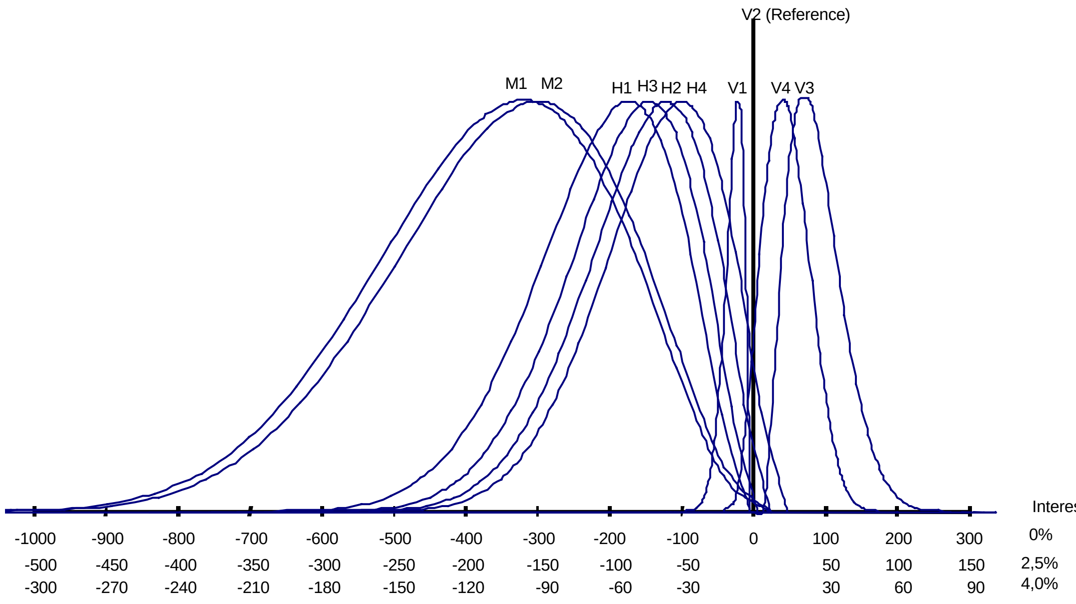



*Figure 9-1 Probability density functions (pdf), kSEK per canister, express cost differences compared to the reference concept KBS-3 V, V2 in the figure. The interest figures given below the diagram are used as discount rate in calculating the present value of the costs.*

One of the main prerequisites for the cost calculations is that all suggested KBS-3 variants are feasible according to presented technical designs. The fact that the design work has reached different technical levels implies that some uncertainties have not been considered in the cost comparison. For example, future R&D work may show that some of the variants might not be feasible without major alterations.

The difference in technical maturity for the different KBS-3 variants is though to some extent reflected by chosen variations in cost for different activities. For example, the risk for cost escalations is judged to be higher for MLH as compared to KBS-3 V.

## 9.3 Summary

In general it can be concluded that it is difficult to predict the cost difference for advanced technical systems in an early development phase. It is especially difficult when the cost differences are in the same order as not unlikely judgements for technical designs or operative prerequisites. The performed calculation has however, been carried out by a methodology that to some extent take into consideration this uncertainty and that also yields a result were the cost difference is expressed as probabilities for different outcomes. The result of the cost evaluation expresses the probable potential for a technical design compared to other designs. The result could in principle, based on a normal risk assessment, constitute a basis for choice of KBS-3 variant.

The main objective with the cost calculations, has been to estimate the difference between KBS-3 H and MLH compared to KBS-3 V. The alternatives V2, H2 and M1 in Figure 9-1 are chosen as for this comparison as they are judged to represent the most plausible technical designs. The result of the comparison is presented in Table 9-1 and

Table 9-2, based on an interest rate of 0 %. The confidence level in Table 9-1, for example 50 %, indicates that the cost difference, with the probability of 50 % is estimated to be equal or higher than the amount given in the table. The table also presents the cost difference as a percentage of the total cost for:

A. Part of the facilities that are included in the comparison of repository variants. Overall cost 750 kSEK for each canister.
B. The deep repository as a whole. Overall cost 3 750 kSEK for each canister
C. All facilities and operations needed for encapsulation and deposition of spent fuel. Overall cost 5 950 kSEK for each canister.

**Table 9-1 Cost difference compared to KBS-3 V for each canister and as percentage of the total costs for A, B and C.**

| | KBS-3 H | | | | MLH | | | |
|---|---|---|---|---|---|---|---|---|
| | | A | B | C | | A | B | C |
| | (kSEK/can)[1] | (% of total cost) | | | (kSEK/can)[1] | (% of total cost) | | |
| Confidence level 50% | -145 | 19 | 3.9 | 2.4 | -340 | 45 | 9.1 | 5.7 |
| Confidence level 70% | -100 | 13 | 2.7 | 1.7 | -250 | 33 | 6.7 | 4.2 |
| Confidence level 90% | -50 | 6.7 | 1.3 | 0.8 | - 150 | 20 | 4.0 | 2.5 |

[1] Based on an interest rate of 0 %.

The total cost differences for disposal of 3 800 canisters are given in Table 9-2. The cost reduction for KBS-3 H compared to KBS-3 V is mainly due to less deposition tunnels (the length of tunnels for each canister is reduced from 6.3 m to 3.5 m and the size of the tunnel is increased from 19.1 $m^2$ to 28.4 $m^2$). The cost reduction for MLH is mainly due to a system without deposition tunnels.

**Table 9-2 Total cost difference compared to KBS-3 V for deposition of 3 800 canisters.**

| | KBS-3 H, MSEK | MLH, MSEK |
|---|---|---|
| Confidence level 50% | -551 | -1292 |
| Confidence level 70% | -380 | -950 |
| Confidence level 90% | -190 | -570 |

# 10 Ranking of KBS-3 variants

## 10.1 Technology

Based on this study, it could be concluded that design and construction of the repository is equally difficult for methods based on vertical and horizontal emplacement.

A difference between vertical and horizontal emplacement is the proposed techniques for deposition of canisters and emplacement of bentonite. For KBS-3 V, it is possible to fill the gap between the bentonite and borehole wall with bentonite pellets in order to obtain requested density and thus a low hydraulic conductivity. Water can subsequently be added to enhance the homogenisation of the bentonite. An issue of great concern for horizontal emplacement is the risk that water leaking along the deposition hole might cause erosion of the bentonite before the blocks have swollen and sealed off the gap between the bentonite and borehole wall. It is recommended that the design of the bentonite barrier for horizontal deposition should be reviewed.

Deposition in individual holes, i.e. KBS-3 V and KBS-3 H, ensures that each deposition is an isolated process, which is favourable from a quality and safety point of view. Further, quality control and surveillance is facilitated due to the possibility of visual inspection.

Vertical deposition of canisters in individual deposition holes is a straightforward method in which gravity is used for lowering the canisters down into the deposition hole.

For deposition according to MLH it has been proposed that bentonite and canisters should be emplaced simultaneously in one package. The deposition of single packages that are pushed along the floor of the deposition holes has several advantages that include simpler handling with less movements and built-in protection for canister and bentonite.

Environmental impact during construction and operation are fairly equal for KBS-3 V and KBS-3 H, but are considered to be more favourable for MLH due to the smaller volume of excavated rock.

In summary, it is concluded that vertical emplacement, in accordance to KBS-3 V, is more robust than horizontal emplacement (KBS-3 H and MLH). The technical difficulties and identified uncertainties are, however, judged to be possible to overcome. It could also be concluded that the development work for horizontal deposition must include tests in full scale, preferably at the Äspö HRL.

## 10.2 Long-term performance and safety

Horizontal emplacement of the buffer (KBS-3 H and MLH) could result in less favourable buffer density, uneven swelling etc. These problems are possibly larger for long deposition holes, i.e. MLH. Development of proper techniques may eliminate this difference between the KBS-3 variants.

The large volume of excavated rock for KBS-3 V and KBS-3 H compared to MLH is unfavourable because all excavations might constitute flow paths for migrating radionuclides. Furthermore, the canister is located relatively close to a tunnel, which is of concern if the requested long-term properties of the backfill are not met. The amount of construction material and stray material like oil, grease that will be left in the repository after closure is also dependent of the excavated rock volumes.

When considering scenarios related to glaciation and seismic events the differences are related to excavated rock volumes and the risk for disturbing one or several canisters by a seismic event. The amount of excavated rock will be considerably larger in KBS-3 V and KBS-3 H compared to MLH. On the other hand, the canisters will be more or less individually deposited in KBS-3 V and KBS-3 H, while MLH is based on disposing a large number of canisters after each other in one deposition hole. The overall conclusion is that an external disturbance that will affect the repository performance is less probable in MLH due to the smaller excavated rock volume, but might have larger impact since several canisters are deposited in each deposition hole

The overall conclusion from the study is that the differences between the KBS-3 variants are generally quite small with respect to the long-term function and safety.

## 10.3 Costs

The estimated costs are lower for variants with horizontal deposition, KBS-3 H and MLH, compared to KBS-3 V.

The cost difference between KBS-3 V and KBS-3 H is fairly small and in the same order as the R&D work necessary to develop KBS-3 H to the same level of technical maturity as KBS-3 V.

The cost for MLH is approximately 950 MSEK lower compared to KBS-3 V (for 3 800 canisters with a confidence level of 70%) The cost data refers to price level of January 1997 and an interest rate of 0%. MLH will require some R&D work to get as mature as KBS-3 V, but the cost difference between the methods is still significant.

## 10.4 Ranking

The ranking of the three KBS-3 variants with respect to the interim items; “technology”, “long-term performance and safety” and “cost” are summarised in Table 10-1.

**Table 10-1 A summary of the results from the comparisons of KBS-3 variants. A ranking of 1 is the best.**

| KBS-3 variant | Technology | Long-term performance and safety | Cost | Ranking summary |
|---|---|---|---|---|
| KBS-3 V | 1 | 1 | 3 | 1 |
| KBS-3 H | 2 | 1 | 2 | 3 |
| MLH | 3 | 1 | 1 | 2 |

Vertical deposition of one canister in each deposition hole, KBS-3 V, was recommended in PASS /SKB, 1992/ and is as well recommended in this study. The concept is robust and each canister has its own barriers in the near field. The possibility for interference between canisters is minimised. Until the persistent quality of serial emplacement of canisters can be clearly demonstrated this is a strong safety argument for the one-canister-per-hole concept. It is, however, not an argument that lends itself to a very rigorous and consistent analysis because it includes a portion of the in-conceived scenarios in the safety assessment.

The performed analyses show that MLH has large potential to be cost attractive compared to KBS-3 V. MLH has also some characteristics that are of advantage for the "long-term performance and safety" that should be considered in more detail. It is therefore recommended to continue to develop MLH.

The cost for KBS-3 H, including necessary R&D work, is on the same order of magnitude as for KBS-3 V. Since no significant advantages have been identified compared to KBS-3 V. it is not recommended to carry out any further development work for KBS-3 H.

The comparisons regarding "long-term performance and safety" and "technology" are based on bored deposition tunnels. The "costs" have been calculated based on excavated deposition tunnels. This difference is not judged to influence the ranking between the KBS-3 variants.

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# Appendix 1:
# Description of KBS-3 V, KBS-3 H and MLH

# 1 Description of KBS-3 V

## 1.1 Layout

The geometric layout of the deep repository for spent fuel consists of a number of deposition tunnels interconnected by tunnels for transport and communication, which are connected to a central service area and ramp/shafts to the ground surface. The exact location of the deposition tunnels and deposition holes will be adapted to local rock conditions. The repository depth is about 500 m below ground surface, in the normal case, but local adaptation will take place at a depth in the range of 400 m to 700 m. The canister with spent nuclear fuel surrounded by a bentonite buffer is deposited in holes bored in the floor of the deposition tunnels. Typical dimensions of transport tunnels, deposition tunnels, and deposition holes are given in Figure 1-1.

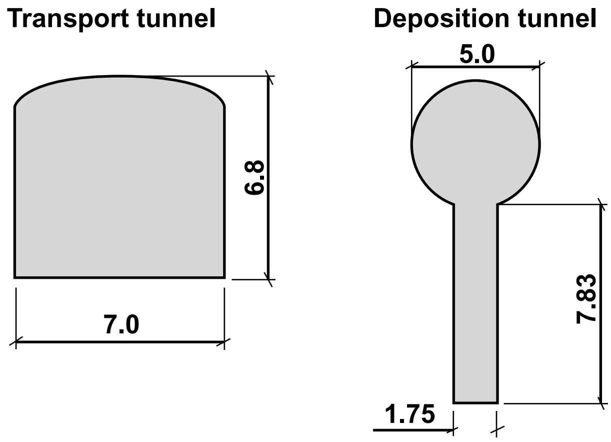


*Figure 1-1 KBS-3 V. Dimensions (in metres) of deposition hole, deposition tunnel (bored) and transport tunnel in the deposition area.*

The repository is planned to be constructed in two stages. The first stage is estimated to accommodate about 5-10 % of the total quantity of spent fuel. The second stage include deposition of the remaining quantity of spent fuel.

During construction, the deposition area is divided into two parts, which makes it possible to perform both construction of deposition tunnels and deposition holes, backfilling of tunnels and deposition of canisters at the same time. The construction of the repository is planned to be carried out in a continuous process in parallel with the deposition of canisters.

## 1.2 Construction

The technique for construction of transport- and deposition tunnels has not yet been decided. The dimensions given in Figure 1-1 are typical for drilled and blasted transport tunnels and deposition tunnels constructed by a tunnel boring machine (TBM).

The ramp down to the repository is assumed to be constructed by tunnel boring technique. When the ramp is completed down to the central area, vertical shafts to ground surface are bored with raise boring technique.

The central area is constructed by drilling and blasting.

The deposition holes have a diameter of 1.75 m with a depth of 7.83 m (theoretical). The boring start with an investigation core hole, drilled in the centre of the deposition hole. If the demands on the geological conditions are fulfilled, the deposition holes are bored to final size, probably with a small size tunnel boring machine, TBM. This technique has been used in the Äspö HRL.

## 1.3 Technique for deposition of canisters

Specially designed equipment will be needed for emplacement of bentonite blocks and deposition of canisters. A study of suitable deposition equipment has been a part of the project JADE. More detailed studies will be needed before it is possible to find a suitable technique for emplacement of bentonite blocks and deposition of canisters. During the progress of the JADE project, SKB made the decision that all handling of canisters should be carried out with a surrounding radiation shielding.

When the canister arrives to the deep repository, it will in a first steep be transported down to the central area at a depth of approximately 500 m below ground. In the central area the canister is transferred from the transportation cask to an enclosing radiation shield that fits into the deposition equipment.

The deposition process starts with the construction of a concrete levelling in the bottom part of the deposition hole. The next step will be emplacement of bentonite block and bentonite rings. For this work, a specially designed vehicle with lifting equipment will be used.

The transportation between the central area and the entrance of the deposition tunnels is assumed to be carried out by a separate vehicle. At the entrance of the deposition tunnels, the cask with the canister is re-loaded to the deposition equipment.

The canister is transported in a horizontal position to the deposition hole. After positioning, the canister is raised to a vertical position by a Cardano movement (simultaneous movement in the x and z direction). The upper part of the deposition hole is used for the Cardano movement. By this type of movement it is possible to reduce the height of the deposition tunnel, and thus reduce the cost for the repository. When the canister is in vertical position the canister is lowered, after positioning, down into the hole in the bentonite barrier. In order to reduce the height of the deposition tunnel, the design suggests a radiation shield that is opened (parted) at the middle of the cask. The radiation shield makes it possible for personnel to work close to the deposition equipment during the entire deposition process. A proposal for deposition equipment is given in Figure 1-3.

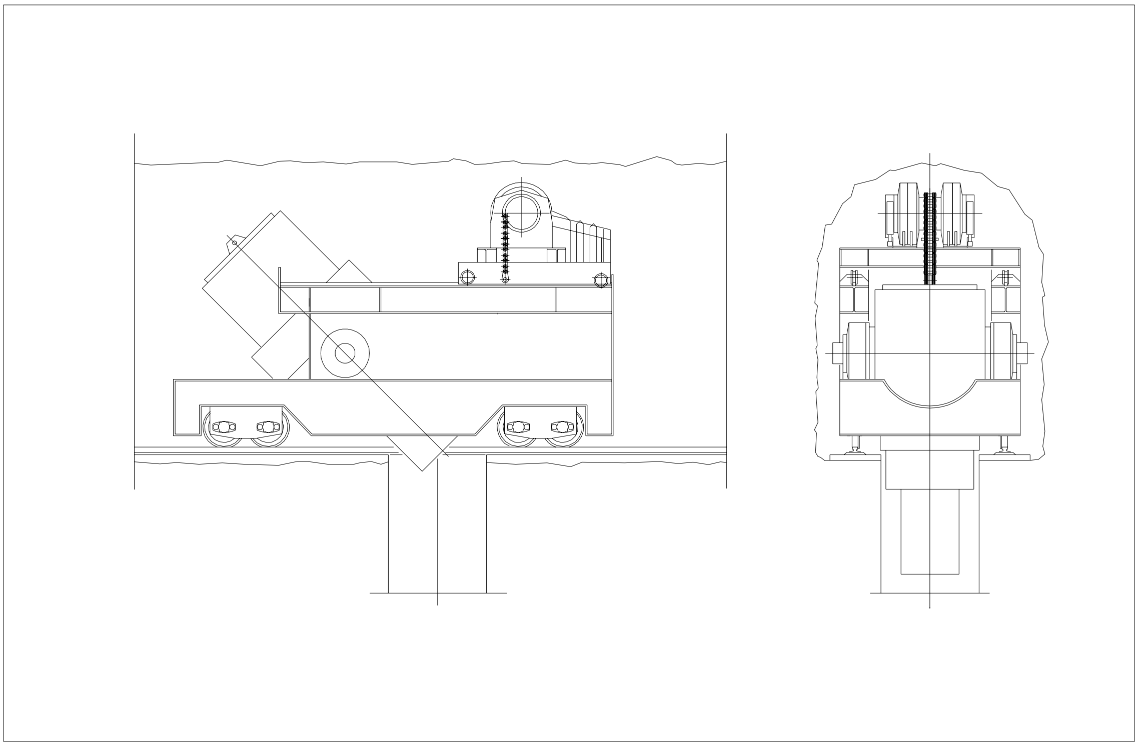

*Figure 1-3 Deposition equipment for KBS-3 V(alternative V6).*

After deposition of the canister, the gap between the bentonite buffer and the borehole wall can be filled with bentonite pellets. Remaining gaps are then filled with water. In next step blocks of bentonite, 1.5 m thick package, is placed above the canister. The remaining part of the deposition hole is filled with a mixture of crushed rock and bentonite, preliminary 15 % bentonite and 85% crushed rock (if the ground water is saline some more bentonite will be needed). A steel plate covers the borehole.

## 1.4 Backfilling and closure

When the deposition of canisters is finished, all temporary equipment in the tunnel such as rails, pipes, etc. are removed and the tunnel is backfilled with a mixture of bentonite and crushed rock (preliminary 15 % bentonite and 85% crushed rock). A temporary plug is constructed at the entrance of the deposition tunnel. This plug may be removed during backfilling of the transport tunnel.

After deposition of all canisters, all remaining parts of the repository are filled with a mixture of bentonite and crushed rock. The ramp and shafts are in some parts sealed by compacted bentonite and/or concrete. The objective with the seals is to prevent groundwater flow along tunnels and rock caverns within the rock mass.

# 2 Description of KBS-3 H

## 2.1 Layout

The geometric layout of the deep repository and the size of the deposition holes according to KBS-3 H will be the same as for KBS-3 V. Compared to KBS-3 V, the canister is deposited in horizontal deposition holes bored in both walls of the deposition tunnels. As a consequence thereof, approximately twice the number of canisters can theoretically be deposited in each deposition tunnel. In order not to increase the temperature at the canister surface and in the bentonite buffer, the spacing between the deposition tunnels must however be increased from 40 m to 60 m.

KBS-3 H requires an increased size of the deposition tunnels compared to KBS-3 V. Typical dimensions of the transport tunnels and deposition tunnels with deposition holes are given in Figure 2-1.

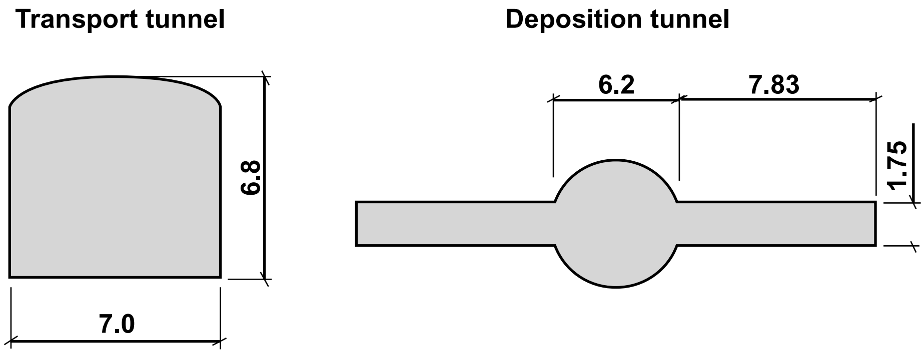


*Figure 2-1 KBS-3 H. Dimensions (in metres) of deposition hole, deposition tunnel (bored) and transport tunnel in the deposition area.*

## 2.2 Construction

The same construction principles will be applicable as for the KBS-3 V.

## 2.3 Technique for deposition of canisters

Different deposition techniques have been studied for KBS-3 H. The R&D work has not yet achieved the technical maturity that is needed for the choice of deposition methodology. Suggested techniques have been evaluated by a group of experts and the opinion is that it is possible to develop a deposition technique that fulfils high demands of quality and safety in the deposition process. The deposition technique chosen as a base for the comparison is shown in Figure 2-2. The deposition hole will be plugged with bentonite after deposition of the canister.

Deposition of canisters and emplacement of bentonite blocks will be carried out according to the same principals as described for the KBS-3 V.

It is assumed that the deposition of canisters and emplacement of bentonite blocks for KBS-3 H could be carried out with the same quality and safety in the deposition process as for KBS-3 V.

It is also possible to modify the deposition technique suggested for the MLH, with deposition of a package consisting of both bentonite blocks and canister, for KBS-3 H.

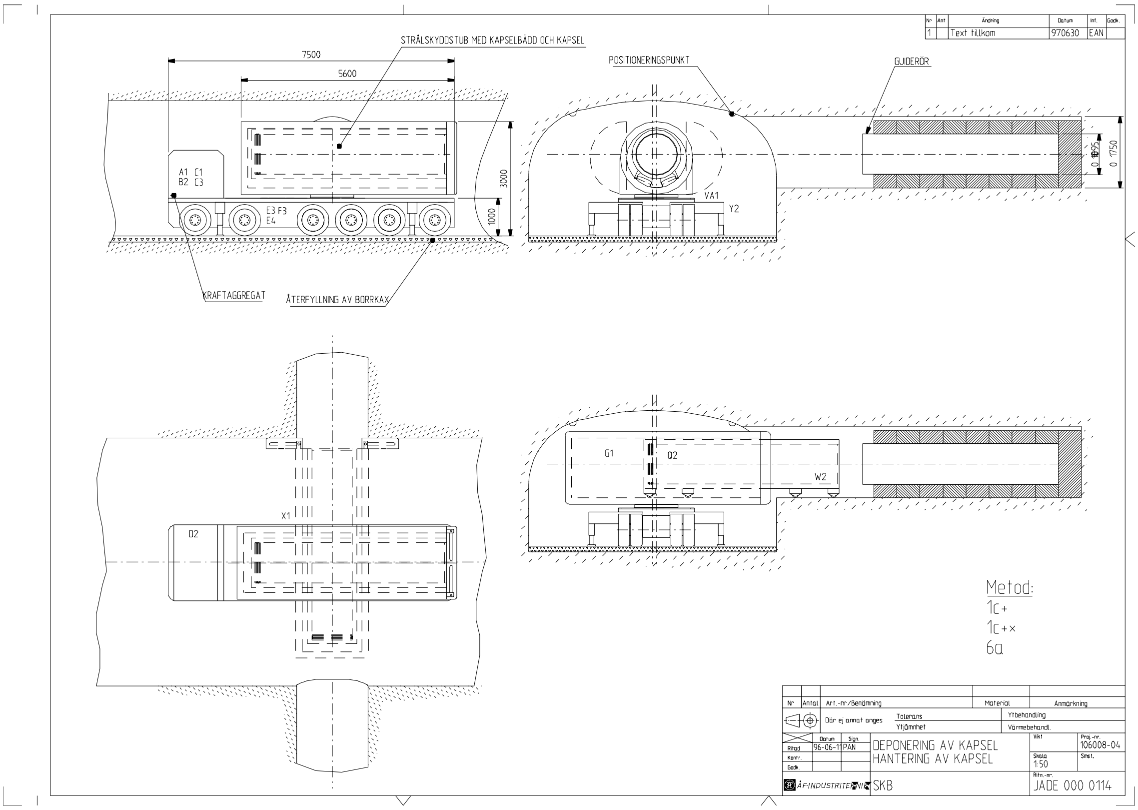


*Figure 2-2    Deposition equipment for KBS-3 H (deposition technique alternative H6).*

## 2.4    Backfilling and closure

Backfilling and closure of the repository after deposition of all canisters will be carried out by the same principles as for KBS-3 V, according to section 1.4 in this appendix.

# 3 Description of MLH

## 3.1 Layout

The geometric layout of the deep repository according to MLH will be the same as for KBS-3 V. Compared to the KBS-3 V, the system of deposition tunnels and deposition holes is replaced by long horizontal deposition holes. The deposition holes are about 250 m long (100 to 500 m long) and bored from the transport tunnels. The canisters are deposited after each other, separated by compacted bentonite.

The deposition holes will be bored by a blind boring technique, probably with a tunnel boring machine, TBM.

The dimensions of the transport tunnel and the deposition holes are shown in Figure 3-1. The spacing between the deposition holes will be 40 m and the distance between the canisters in the hole will be 1.2 m according to temperature calculations. The width of the transport tunnel is suggested to be increased with 1 m for MLH compared to KBS-3 V due to the need for more space in the tunnel during boring.

MLH is less mature as compared to KBS-3 V. The required R&D work involves all parts of the system such as boring of the deposition holes, technique for deposition of canisters and emplacement of bentonite and techniques for rock support and grouting in the small deposition holes. An issue of special interest for MLH is if the water inflow into the deposition hole will influence the final conditions of the bentonite barrier.

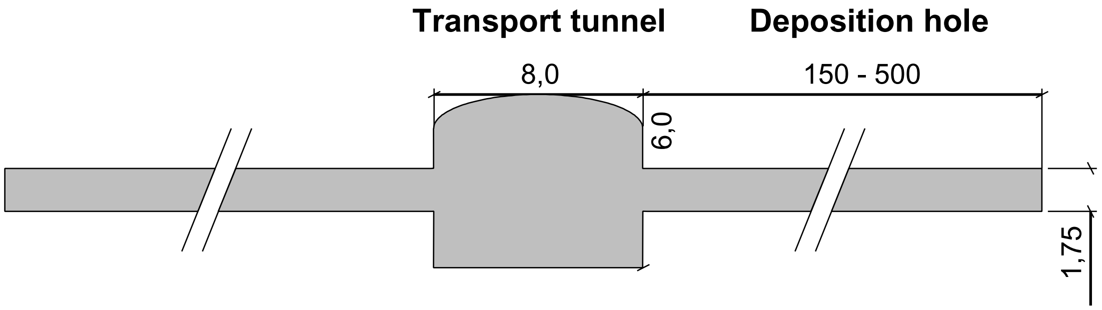


*Figure 3-1 MLH. Dimensions (in metres) of deposition hole and transport tunnel in the deposition area.*

## 3.2 Construction

The same construction principles will be applicable as for KBS-3 V for the construction of the ramp, shafts, central area and transport tunnels.

The boring of deposition holes is planned to be performed with a tunnel boring machine, TBM. A suitable TBM is shown in Figure 3-2. This TBM has been used to bore a small tunnel with a diameter of 1.65 m in hard rock in Montreal. Excavated rock chips are transported out from the tunnel by a conveyor system. Even though the machine has a fairly small diameter it is possible to change cutters at the face in the tunnel without moving the machine out from the tunnel. A prerequisite for boring of deposition holes is that the machine is operated by remote control from the transport tunnel.

The TBM shown in Figure 3-2 has also been used for the boring of vertical deposition holes, diameter 1.75 m, in the Äspo HRL during 1998 and 1999. For this type of boring, the normal jacks have been change to jacks that are pressed towards casing pipes that are placed above the cutter head.

The boring of the deposition hole will be preceded by drilling of a core hole in the centre of the deposition hole. The final decision of boring the deposition hole and the length of the hole will be based on e.g. the geological conditions obtained from the result of the core drilling. Based on the core hole it is also possible to plan for necessary grouting and rock support works.

For grouting and rock support works it will be necessary to manufacture special equipment suitable for works in a long small circular tunnel.


*Figure 3-2 Tunnel boring machine suitable for boring of deposition tunnels for the MLH system (from /Wallis, 1997/).*

## 3.3 Technique for deposition of canisters

Different deposition techniques have been studied for MLH. The R&D work has not yet achieved the technical maturity that is needed for the choice of deposition methodology. Suggested techniques have been evaluated by a group of experts, see Appendix 2, and the opinion is that it is possible to develop a deposition technique that fulfils high demands of quality and safety in the deposition process.

During the development work some important prerequisites for the design of the deposition equipment have been identified:

- The technical system should be robust and with few movable parts.
- Deposition of a packages consisting of bentonite buffer and canister is desirable.
- The deposition technique should be lenient to the rock surface in the tunnel. This implies that there should be a slipping device between the package bentonite-canister and the tunnel floor.
- The bentonite should be protected towards dripping water during emplacement.

A suitable technique for deposition of a package of bentonite blocks and canister has been studied. The package is surrounded by a net of copper bars that holds the package together and constitutes a slipping surface during the transportation in the deposition hole. The package is pushed ahead in the deposition hole by equipment similar to the jacking system used by a TBM. A schematic illustration of deposition of a package with bentonite blocks and canister is shown in Figure 3-3.

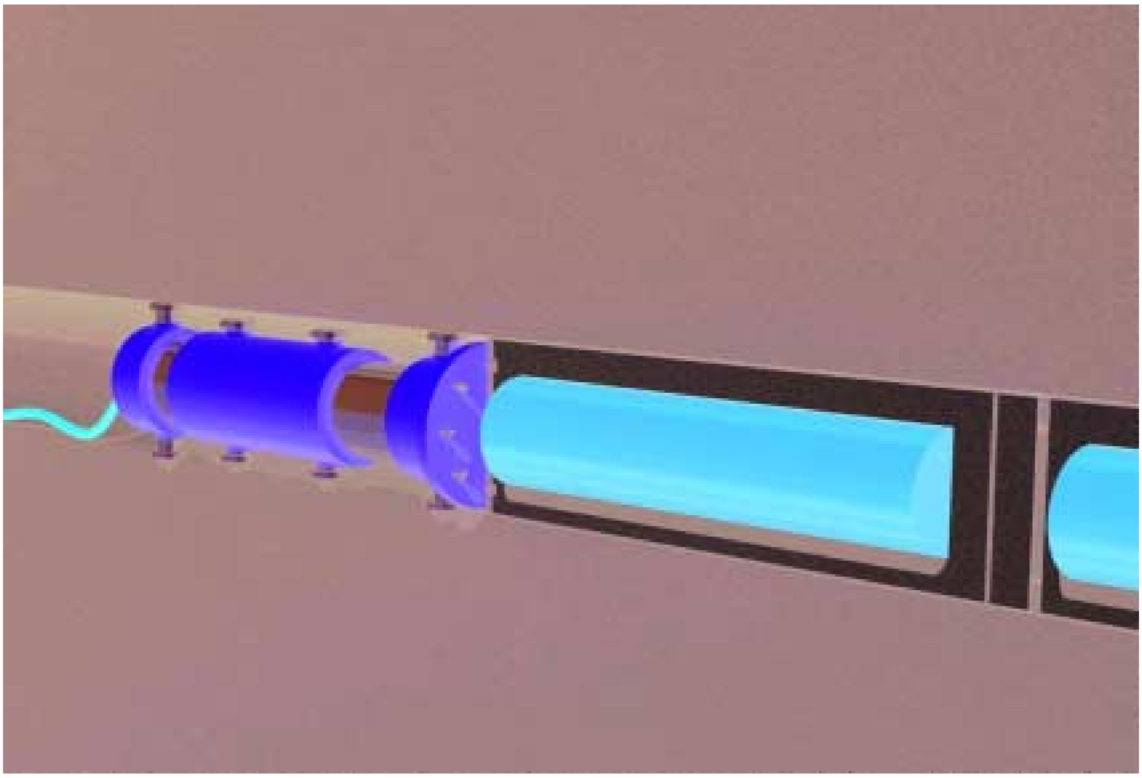

*Figure 3-3 Deposition of a package canister-bentonite in long horizontal deposition holes.*

## 3.4 Backfilling and closure

In sections of the deposition hole where no canisters are to be emplaced, e.g. in parts with unsuitable rock conditions, the deposition holes are backfilled with compacted bentonite. The same equipment as for the package bentonite-canister will emplace the bentonite.

Backfilling and closure of the repository after deposition of all canisters will be carried out in the same way as for KBS-3 V.

# Appendix 2:
# Machine advisory group

# Machine Advisory Group

A Machine Advisory Group was set up within the JADE project and was given the following tasks:

- Discuss, evaluate and recommend designs of machine equipment for deposition of bentonite and canisters with spent fuel.
- Discuss, evaluate and recommend strategies for the development of these machine equipment.
- Discuss, evaluate and recommend production techniques for these machine equipment.
- Take part in the discussion and evaluation of other questions concerning machines that are brought to the attention of the group.

The members of the machine advisory group were:

- Bo Nirvin, Forsmarks Kraftgrupp-SFR.
- Karl-Erik Niva, Kiruna Truck.
- Stig Pettersson, SKB.
- Josef Piroska.
- Håkan Sandstedt, Scandiaconsult – Secretary.
- Staffan Sunnersjö, Institutet för Verkstadsteknisk Forskning.
- Christer Svemar, SKB – Chairman.

Presentations were given to the machine advisory group by:

- Pal Kalbantner, ÅF-Industriteknik - Horizontal disposal.
- Lars Jansson, VBB Anläggning - Vertical disposal.

The machine advisory group met 5 times during 1996 and 1997.

# Appendix 3:
# Technical specifications for
# KBS-3 V, KBS-3 H and MLH

# Technical specifications for KBS-3 V, KBS-3 H and MLH

The comparison is based on a preliminary design derived from the PLAN works, mostly from the report PLAN 97 /SKB, 1997/, and development works carried out within the JADE project. The development work carried out as a part of JADE were mostly concentrated on techniques for the deposition of canisters and a review of MLH.

Technical data, background information and assumptions for the three repository concepts are given in Table 1 and Table 2.

**Table 1 Technical specifications of bedrock, spent nuclear fuel, canister, and repository layout.**

| Part of the repository | KBS-3 V | KBS-3 H | MLH |
|---|---|---|---|
| **Bedrock** | | | |
| Repository level | 500 | 500 | 500 |
| Initial rock temperature, °C | 10 | 10 | 10 |
| Temperature gradient, °C/km | 13 | 13 | 13 |
| Density kg/m$^3$ | 2700 | 2700 | 2700 |
| Coefficient of thermal conductivity, W/m,K | 3.6 | 3.6 | 3.6 |
| Heat capacity, MJ/m$^3$,K | 2.4 | 2.4 | 2.4 |
| **Spent nuclear fuel** | | | |
| BWR elements | 12 | 12 | 12 |
| **Canister** | | | |
| Position | Vertical | Horizontal | Horizontal |
| Size L/Ø (m) | 4.83/1.05 | 4.83/1.05 | 4.83/1.05 |
| Power, W/m$^2$ canister surface | 100 | 100 | 100 |
| Power decay with time | See SKB TR 91-61 | See SKB TR 91-61 | See SKB TR 91-61 |
| Coefficient of thermal conductivity, W/m,K | 390 | 390 | 390 |
| Heat capacity, MJ/m$^3$,K | 2.4 | 2.4 | 2.4 |
| **Repository layout** | | | |
| Deposition tunnels, L (m) | 250 | 250 | - |
| Deposition tunnels, Ø (m), bored tunnels[1)] | 5.0 | 6.2 | - |
| Deposition tunnels, W x H (m), blasted tunnels[2)] | 4.2*5 | 6.2*5 | - |
| Spacing between deposition tunnels (m) | 40 | 60 | - |
| Diameter of deposition holes Ø (m) | 1.75 | 1.75 | 1.75 |
| Length of deposition holes L (m) | 7.83 | 7.83 | 250 |
| Inclination | Vertical | Max 5 degrees | Max 5 degrees |
| Spacing between deposition holes (m) | 6.3 | 7.1 (in both walls) | 40 |
| Spacing between canisters (m)[3)] | 6.3 | 7.1 (in both walls) | 1.2 |
| Transport tunnel W x H (m) | 7*6.8 | 7*6.8 | 8*6 |
| Assumed extension, km$^2$ | 2 | 2 | 2 |

1) Basis for comparison of technology and long-term performance and safety.
2) Basis for comparison of costs.
3) Distance end to end for MLH.

**Table 2 Technical specifications of bentonite barrier and tunnel backfill**

| Part of the repository | KBS-3 V | KBS-3 H | MLH |
|---|---|---|---|
| **Bentonite barrier** | | | |
| Material | Compacted bentonite with high water content | Compacted bentonite with high water content | Compacted bentonite with high water content |
| Thickness during deposition, sides/bottom/top (m) | 0.29/0.5/1.5 | 0.31/0.5/1.5 | 0.31/0.5/0.6 |
| Thickness after homogenisation, sides/bottom/top (m) | 0.35/0.5/1.5 | 0.35/0.5/1.5 | 0.35/0.5/0.6 |
| Density kg/$m^3$ | 2000 | 2000 | 2000 |
| Coefficient of thermal conductivity, year 1, W/m, K | 1.05 | 1.05 | 1.05 |
| Coefficient of thermal conductivity, year 15, W/m, K | 1.15 | 1.15 | 1.15 |
| Coefficient of thermal conductivity, MJ/$m^3$,K | 2.20 | 2.20 | 2.20 |
| **Tunnel backfill** | | | |
| Plug between bentonite and deposition tunnel | 1 m bentonite/ crushed rock (15/85) | 1 m bentonite/ crushed rock (15/85) | - |
| Tunnel backfill (weight %) | Bentonite/crushed rock (15/85) | Bentonite/crushed rock (15/85) | - |
| Density, kg/$m^3$ | 1700 | 1700 | 1700 |
| Coefficient of thermal conductivity, year 15, W/m, K | 1.00 | 1.00 | 1.00 |
| Heat capacity, MJ/$m^3$,K | 1.75 | 1.75 | 1.75 |
| Plug towards the transport tunnel | Concrete | Concrete | Concrete |

# Appendix 4:
# Specification of variation of data for cost calculations according to “the Successive Principle”

# Specification of variation of data for cost calculations according to "the Successive Principle"

The used calculation method, "the Successive Principle" implies that the result of the calculation includes measures of the relative uncertainty for different objects in the calculation. The largest uncertainties will be distinguished and studied in more detail. The process is repeated and the calculation gradually converges towards a cost estimate with less uncertainty. The calculation principle is specially developed to be used in early project faces when several prerequisites for a project is uncertain.

The " Successive Principle", as used by SKB for calculation of the cost for the deep repository, is based on a systematic break down of the cost into a number of well defined activities. The activities could constitute a part of the repository or different actions that will influence the cost for the repository. The uncertainties are evaluated for all activities. In the calculation, three cost figures are assessed for all defined activities; maximum, average and minimum cost. Based on these three figures various probability density functions could be assessed which describes the probability for different costs. The final calculation is carried out by a Monte Carlo-simulation. Based on the performed simulation (2000 realisations) the result is evaluated according to established statistical procedures.

According to the principle "the Successive Principle", the cost calculation has been divided into the following activities:

1) Deposition holes, boring.
2) Deposition holes, additional works.
3) Deposition tunnels, construction.
4) Deposition tunnels, back filling.
5) Deposition tunnels, construction works in the tunnels.
6) Transport tunnels, all activities.
7) Facility for re-loading, all activities.
8) Deposition equipment, R&D.
9) Deposition equipment, manufacturing and service.
10) Operation of the deep repository (personnel and material).
11) Bentonite (emplacement of bentonite is included in 10).

General variations can influence several of the activities described above. Calculation uncertainties have been considered by including 11 variations. A summary of considered variations and selected data for KBS-3 V, KBS-3 H and MLH are given in Table 1.

**Table 1 Considered variations in the cost calculation**

| Variation | | Min | Average (reference) | Max |
|---|---|---|---|---|
| **Variation 1.** The number of canisters and time schedule for deposition | KBS-3 V<br>KBS-3 H<br>MLH | 3.000<br>3.000<br>3.000 | 3.800<br>3.800<br>3.800 | 4.500<br>4.500<br>4.500 |
| **Variation 2.** Temperature in the canister as a result of the time schedule. Heat power at the canister surface. $W/m^2$ | KBS-3 V<br>KBS-3 H<br>MLH | 90<br>90<br>90 | 100<br>100<br>100 | 110<br>110<br>110 |
| **Variation 3.** Initial temperature in the bed rock at the repository level. °C | KBS-3 V<br>KBS-3 H<br>MLH | 5<br>5<br>5 | 10<br>10<br>10 | 15<br>15<br>15 |
| **Variation 4.** Additional length of transport and deposition tunnels, % extra length | KBS-3 V<br>KBS-3 H<br>MLH | 9<br>11<br>9 | 10<br>12<br>12 | 11<br>14<br>15 |
| **Variation 5.** Temperature parameters for bentonite and bed rock. Temperature increase at canister surface. °C | KBS-3 V<br>KBS-3 H<br>MLH | 75<br>75<br>75 | 70<br>70<br>70 | 65<br>65<br>65 |
| **Variation 6.** Accepted temperature at the canister surface. °C | KBS-3 V<br>KBS-3 H<br>MLH | 100<br>100<br>100 | 90<br>90<br>90 | 80<br>80<br>80 |
| **Variation 7.** Size of deposition tunnels. ± in % compared to theoretical size | KBS-3 V<br>KBS-3 H<br>MLH | -20<br>-20<br>-20 | 0<br>0<br>0 | +20<br>+20<br>+20 |
| **Variation 8.** Additional length of deposition tunnels due to not acceptable rock conditions. ± in % compared to reference length | KBS-3 V<br>KBS-3 H<br>MLH | -10<br>-12<br>-12 | Ref. length<br>Ref. length<br>Ref. length | +20<br>+20<br>+20 |
| **Variation 9.** Material for back filling. | KBS-3 V | Crushed rock | Crushed rock/bent. 85/15 | Quartz sand/bent. 70/30 |
| | KBS-3 H | Crushed rock | Crushed rock/bent. 85/15 | Quartz sand/bent. 70/30 |
| | MLH | Crushed rock | Crushed rock/bent. 85/15 | Quartz sand/bent. 70/30 |
| **Variation 10.** Price for bentonite ± in % compared to PLAN 97 | KBS-3 V<br>KBS-3 H<br>MLH | -30<br>-30<br>-30 | Reference cost<br>Reference cost<br>Reference cost | +50<br>+50<br>+50 |
| **Variation 11**[1]**.** General uncertainties in the cost calculation. ± in % compared to estimated reference cost | KBS-3 V<br>KBS-3 H<br>MLH | -20<br>-20<br>-20 | Reference cost<br>Reference cost<br>Reference cost | +30<br>+30<br>+30 |

[1)] The difference in cost for R&D work, besides the development of equipment for deposition of canisters and emplacement of bentonite blocks, is included in variation 11.

Cost calculations have been performed for 10 deposition alternatives. The alternatives differ with respect to selection of equipment and technique for deposition or other principle differences that influence the costs, especially the volume of tunnels. A compilation of considered alternatives and typical tunnel dimensions for these alternatives are given in Table 2. The main alternatives in the performed comparison of costs are alternatives V2, H2 and M1 in Table 2.

**Table 2 Considered alternatives with typical tunnel dimensions**

| | Alt. | Description | Deposition tunnel w × h (m) | Transport tunnel w × h (m) |
|---|---|---|---|---|
| KBS-3 V | V1 | Railbound deposition vehicle. Deposition of an unshielded canister behind a radiation shield. | 4,0 × 4,5 | 7,0 × 6,3 |
| | V2 | Railbound deposition vehicle. Deposition of canister with a devisable radiation shield. | 4,2 × 5,0 | 7,0 × 6,8 |
| | V3 | Railbound deposition vehicle. Deposition of a canister/bentonite package with a devisable radiation shield. | 4,7 × 6,2 | 7,0 × 8,0 |
| | V4 | Fork lift vehicle. Deposition of a standing canister with a radiation shield. | 4,5 × 6,1 | 7,0 × 7,9 |
| KBS-3 H | H1 | Railbound deposition vehicle. Deposition of an unshielded canister behind a radiation shield. | 4,0 × 4,5 | 7,0 × 6,3 |
| | H2 | Railbound deposition vehicle. Deposition of canister with a radiation shield. | 6,2 × 5,0 | 7,0 × 6,8 |
| | H3 | Fork lift vehicle. Deposition of a canister with a radiation shield. | 6,5 × 5,0 | 7,0 × 6,8 |
| | H4 | Railbound deposition vehicle. Deposition of a canister/bentonite package with a radiation shield. | 6,6 × 5,5 | 7,0 × 7,3 |
| MLH | M1 | Deposition of a canister/bentonite package. Normal margin for space not used for deposition. | ---- | 8,0 × 6,0 |
| | M2 | Deposition of a canister/bentonite package High margin for space not used for deposition. | ---- | 8,0 × 6,0 |