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Project on Alternative Systems Study – PASS. Comparison of technology of KBS-3, MLH, VLH and VDH concepts by using an expert group

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PROJECT ON ALTERNATIVE SYSTEMS STUDY - PASS. COMPARISON OF TECHNOLOGY OF KBS-3, MLH VLH AND VDH CONCEPTS BY USING AN EXPERT GROUP

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author(s) and do not necessarily coincide with those of the client.

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PROJECT ON ALTERNATIVE SYSTEMS STUDY-PASS

COMPARISON OF TECHNOLOGY OF KBS-3, MLH VLH AND VDH CONCEPTS BY USING AN EXPERT GROUP

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ABSTRACT (ENGLISH)

This report constitutes a technical comparison and ranking of four repository concepts for final disposal of spent nuclear fuel, that have been studied by SKB: KBS-3, Medium Long Holes (MLH), Very Long Holes (VLH) and Very Deep Holes (VDH). The technical comparison is part of the project "Project on Alternative Systems Study, PASS", which was initiated by SKB With the objective of presenting a ranking of the four concepts. Besides this comparison of Technology the ranking is separately made for Long-term Performance and Safety, and Costs before the merging into one verdict.

The ranking regarding Technology was carried out in accordance with the method Analytical Hierarchy Process, AHP, and by the aid of expert judgement in the form of a group consisting of six experts. The AHP method implies that the criteria for comparison are ordered in a hierarchy and that the ranking is carried out by pairwise comparison of the criteria. In the evaluation process a measure of the relative importance of each criterion is obtained.

The result of the expert judgement exercise was that each expert individually ranked the four concepts in the following order with the top ranked alternative first: KBS-3, MLH, VLH and VDH. The common opinion among the experts was that the top ranking of KBS-3 is significant and that the major criteria used in the study could change substantially without changing the top ranking of KBS-3.

ABSTRACT (SWEDISH)

Denna rapport utgör en teknisk jämförelse och rangordning av fyra olika djupförvarings-koncept för slutlig förvaring av det långlivade kärnkraftsavfallet som har studerats av SKB: KBS-3, Medellånga tunnlar (MLH), Långa tunnlar (VLH) och Djupa borrhål (VDH). Den tekniska jämförelsen ingår i projektet "Projekt AlternativStudier för Slutförvar" (PASS) som initierades av SKB för att rangordna de olika koncepten. Förutom att utvärdera och jämföra teknik har separata jämförelser utförts för långsiktig funktion och säkerhet samt kostnader. I den slutliga jämförelsen av koncepten sammanvägs dessa olika delar i en slutlig rangordning av koncepten.

Jämförelse av Teknik har utförts med hjälp av metoden " Analytical Hierarchy Process, AHP," och "expert judgement". Expertgruppen som utsågs bestod av sex personer. Metoden innebär att kriterierna för jämförelse organiseras i en hierarki och jämförs parvis. Genom metoden erhålles ett mått på den relativa betydelsen hos varje kriterium.

Resultatet av rangordningen innebar att alla experter placerade koncepten i följande ordning med det högst rangordnade konceptet först: KBS-3, MLH, VLH och VDH. Den allmäna uppfattningen bland experterna var att placeringen av KBS-3 som det första alternativ är stabil och att de förutsättningar som använts i jämförelsen kan ändras avsevärt utan att topplaceringen av KBS-3 ändras.

SUMMARY

This comparison and ranking of repository concepts is a part of the project "Project on Alternative Systems Study (PASS)" that was initiated by SKB in order to evaluate and compare different repository concept for final disposal of spent nuclear fuel. The evaluation includes all issues related to technology, safety and economy. This report constitutes a technical comparison of the following four concepts and includes all activities regarding design, construction and operation (deposition of canisters) as well as aspects on post-closure:

- KBS-3. Deposition of canisters with spent nuclear fuel in deposition boreholes drilled in the floor of tunnels at a depth of about 500 m below ground surface. The deposition tunnels have a length of about 250 m
- Medium Long Holes (MLH). Horizontal deposition of the same canister as for the KBS-3 concept in parallel tunnel system, each tunnel with a length of about 250 m
- Very Long Holes (VLH). Deposition of the spent fuel in fairly large canisters in several km long horizontal, bored tunnels
- Very Deep Holes (VDH). Deposition of canisters with spent nuclear fuel in deep boreholes at a depth of between 2000 and 4000 m below ground surface

The comparison was made by the aid of six experts in an expert judgement exercise. Based on literature survey this exercise was carried out according to the method Analythical Hierarchy Process which features that the criteria for comparison are ordered in a hierarchy and that the ranking is carried out by pairwise comparison between criteria. By a specific evaluation process a measure on the relative importance of each criterion is obtained. In this study the experts made the exercise individually and took part in each others result first during a later group discussion. The result of the expert judgement presented in figure1 shows that all six experts ranked the concepts in the following order; KBS-3, MLH, VLH and VDH.

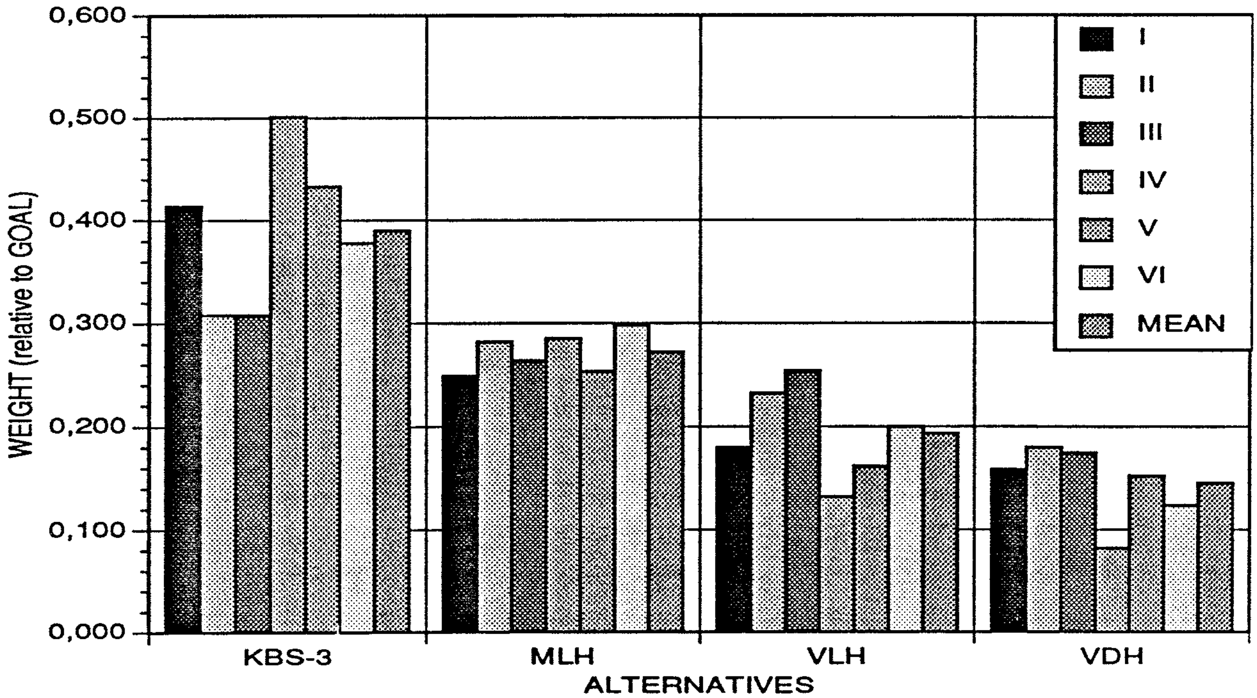

Figure 1 Ranking of repository concepts

The robustness of the result was analysed according to the hierarchic structure model and the choice of experts. This evaluation shows that the ranking result is not sensitive to changes in the model or small changes of the individual judgements in the ranking (pairwise comparison). Some fear was raised in the beginning that each expert would take the same views since they have been working together with SKB for a long time. This was analysed and the result shows that the correlation between the experts is small and that they have made their judgements independently of one another. Since the experts took part in the design of the hierarchic structure and also had a possibility to make changes in the ranking after a group discussion, the risk for misunderstandings of the meaning of different criteria and the ranking procedure was pretty much eliminated.

The ranking procedure was completed with a meeting of the expert group. The common opinion among the experts was that the ranking result is logical specially with respect to KBS-3 in the top position. This verdict stands also for significant changes in the major technical parameters.

The main technical advantage with the KBS-3 concept is that the canisters are placed individually in vertical boreholes at the bottom of a system of storage tunnels. After the canister is placed in position and surrounded with bentonite in the deposition hole the canister is shielded from radiation and the continuing disposal work in the deposition tunnel could be carried out with no exposing of man. The comparatively large size of the deposition tunnels will facilitate transportation of canisters and also be favourable if any work needs to be carried out during the deposition procedure such as retrieving a stuck canister. An advantage is also that positioning of bentonite around the canisters could be carried out with good quality control, since the bentonite is placed in position before deposition of the canister.

Compared to the KBS-3, the suggested deposition procedure for the two other mined repository concepts (MLH and VLH) are based on a non completed operation where the canisters are stored after one another in a horizontal position. For transportation and deposition of canisters in a long, circular (1.6 or 2.4 m in diameter) tunnel, a fairly more complicated transport systems will be needed than for KBS-3. All reverse operations due to any problem during transportation or deposition will be specially difficult to handle in VLH because of the very limited space in the tunnel. It is also negative for the concept that radiation protection around the canister will not be possible in the disposal tunnel due to the small space between the canister and the tunnel walls.

Compared to the mined repository concepts the VDH concept is based on a different and more novel technology, the drilling of deep, large diameter boreholes. Suggested technique for deposition of canisters involves several unproven operation steps with risk for damage of one or several canisters. As deposition is carried out without visual control the risk for storage of a damaged canister is larger compared to the other concepts. Deposition and sealing of the repository constitutes a major technical difficulty in the VDH concept. Two other negative prerequisites of the VDH concept are the vast number of canisters and the large areal distribution of the repository that make this concept more vulnerable for sabotage.

Conditions for geological investigations are fairly similar for the three mined repository concepts. The VDH concept, however, must be based on a more vague geological model due to the great depth down to the repository and the large area distribution.

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APPENDICES

1 INTRODUCTION

During the last two decades the Swedish Nuclear Fuel and Waste Management Co, SKB, has studied different repository concepts for the final disposal of the spent nuclear fuel. The KBS-3 concept was presented in 1983 by SKB as required by Swedish legislation before a charging permit could be granted for the latest two nuclear power reactors taken into operation (Orskarshamn 3 and Forsmark 3). After domestic and international peer reviews the Swedish government declared that the concept satisfies the safety and radiation protection requirements set forth in the law. The KBS-3 concept /1-1/, now constitutes reference concept for the Swedish nuclear power program and a basis for the annual cost calculations for deciding the appropriate fee on nuclear power electricity for the back-end cycle.

Since 1984 SKB has developed and evaluated some other promising concepts. It has been possible to prove that also the alternative concepts have a good potential to fulfil high safety demands.

During the years 1986 to 1989 the WP-Cave concept was evaluated and compared to the reference concept. At that time the WP-Cave was the alternative that was most developed after the KBS-3. The result showed that KBS-3 featured major advantages over the WP-Cave system and consequently studies of the WP-Cave system were not continued.

Three other sub-surface repository concepts have also been developed and are presented below in the order that they have been studied:

- Very Deep Holes (VDH). Deposition of canister with spent fuel in deep boreholes at a depth of between 2000 and 4000 m below ground surface /1-2 /
- Very Long Holes (VLH). Deposition of spent fuel in fairly large canisters in long horizontal, bored tunnels / 1-3 /
- Medium Long Holes (MLH). Horizontal deposition of the same canister as for the KBS concept in a parallel tunnel system, each tunnel with a length of about 250 m /1-4/

For each of the developed systems different canister designs are considered. The options are, however, few for the VDH and VLH. The KBS-3 size of canister features several in principle different alternatives.

The development of the alternative repository systems and the different canister alternatives is conducted within the frame of "Project on Alternative Systems Study (PASS), with the objective of presenting a ranking of alternatives being currently studied. The ranking of repository systems is primarily carried out for three different headings:

- Technology (for construction and disposal)
- Long term performance and safety
- Costs

Evaluation and choice of suitable canisters for the different concepts have also been a part of the PASS project but this study is presented in a separate report. This technical comparison is based on preferred and recommended canister for each concept.

This report constitutes a technical comparison of the four different concepts and includes all activities regarding design, construction and operation (deposition of canisters) as well as aspects on post-closure (human intrusion). The ranking for each of the above headings are eventually to be merged together into one ranking.

2 TECHNICAL DESCRIPTION OF REPOSITORY CONCEPTS

2.1 General

This chapter includes a brief description of the four repository concepts that is a part of this technical comparison and ranking of repository concepts. For a detailed presentation of the concepts see the following SKB technical reports:

- KBS-3, SKB Kostnader för kärnkraftens radioaktiva restprodukter, PLAN 92 /2-1/
- MLH, SKB Projekt AlternativStudier för Slutförvar (PASS) /2-2/
- VLH, SKB Technical Report TR 91-35 /2-3/
- VDH, SKB Technical Report TR 89-39 /2-4/

In order to make a relevant ranking it has been necessary to modify the repository layouts so that the comparison is based on system specific differences instead of different prerequisities. As an example, all mined repositories will be designed with a ramp down to the repository level instead of a vertical shaft and the backfill around the canisters will consist of the same type of bentonite.

2.2 Reference concept according to the KBS-3 method

A repository concept according to the KBS-3 principle / 2-1 / consists of a system of tunnels and drifts located at a depth of about 500 m below ground surface, see figure 2-1 (two shafts will be replaced by one ramp). The repository will be located to a block of rock surrounded by major fracture zones. The bedrock within the defined rock block should be favourable for repository construction and should serve as a geological barrier for nuclide migration to the biosphere.

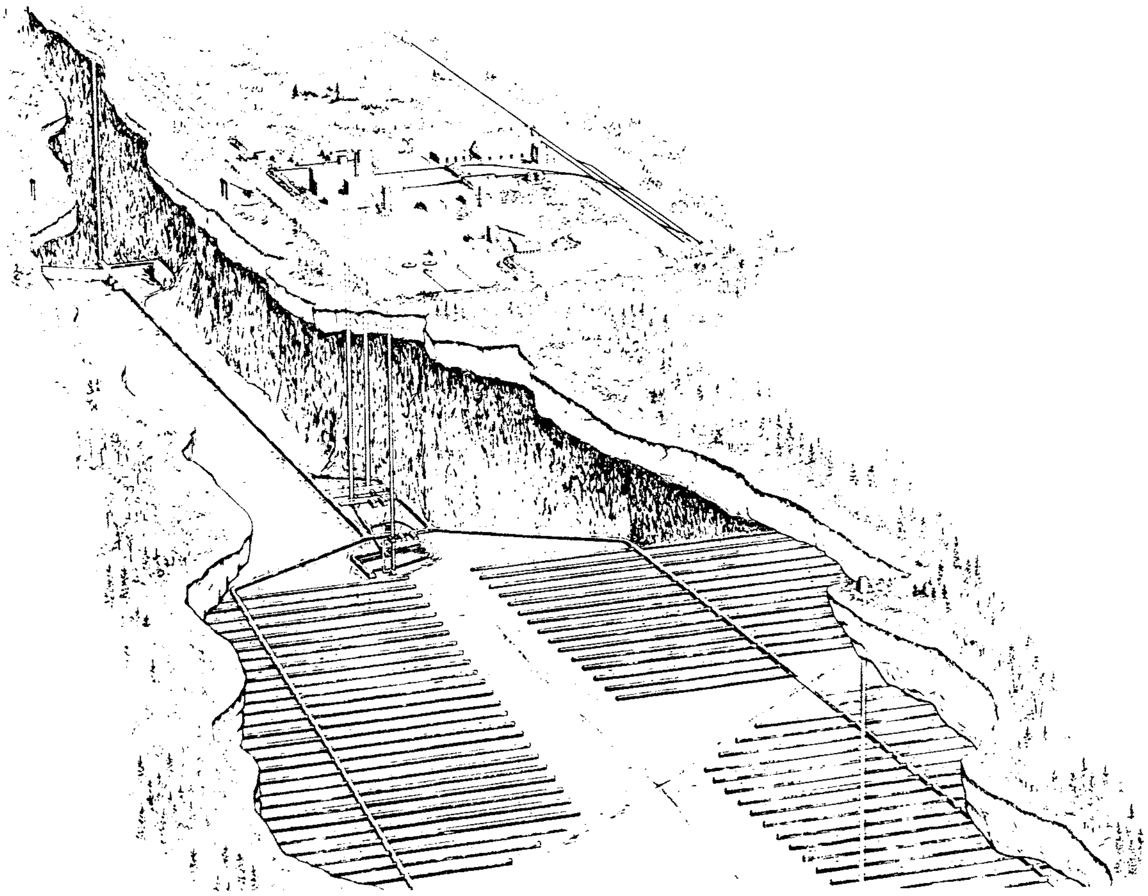


Figure 2-1 View of a repository according to the KBS-3 principle

The spent fuel will be isolated in copper-steel canisters which are expected to resist corrosion in the order of a million years. The canisters are placed in vertical boreholes drilled in the floor of a horizontal tunnel system approx. 6 m apart surrounded by highly compacted bentonite clay, see Figure 2-2. After homogenization, the average hydraulic conductivity of the bentonite will be in the range of 10^{-12} m/s depending on the ground water quality. This is satisfactory for prosiding mechanical support of the canister against plausible displacements in the nearfield rock, and migration resistance for nuclides in case of canister penetration. After emplacement of the waste canisters the entire drifts, tunnels and access shafts will be filled with a mixture of sand and bentonite and the repository will be left unattended for years to come.

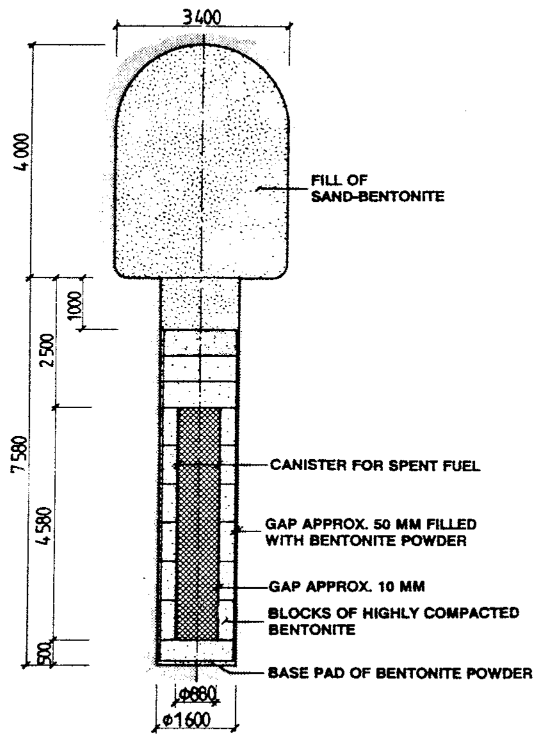


Figure 2-2 Deposition hole with canister, buffer material and backfill of the storage tunnel

The area needed for a repository according to the KBS-3 system is approx. 1x1 km including a respect distance of 100 m to major fracture zones. The final layout will, however, be dependent on local geological conditions of the chosen block of rock. A minimum spacing of 25 m is required between the storage tunnels in order not to exceed a temperature of 100° C in the bentonite barrier.

The sub-surface repository facility consists of a system of parallel deposition tunnels with belonging transport tunnels and service area. The access down to the repository is suggested to consist of one ramp and two vertical shafts. The ramp will constitute the main transportation system between the ground surface and the repository level. The vertical shafts will be needed for ventilation, supplies etc.

During operation the repository is separated into two parts in order to allow construction and deposition of canisters at the same time.

The ramp down to the repository level is suggested to be constructed by TBM-boring technique with an inclination of 1:7. Transportation of muck etc could for example be carried out by the newly developed railbound transportation system Rapid Haulage System (RHS). The system is developed by the Swedish contractor Kraftbyggarna AB and is currently used together with TBM-boring of a long tunnel at Klippen hydro power station.

At the repository level, the vertical shafts will be constructed by conventional raise boring technique. All construction work at the repository level is suggested to be carried out by drill and blast. The deposition boreholes will be drilled with a machine similar to raise boring equipment but designed for blind boring. The boring to the final size will be preceded by core drilling (pilot hole) in order to evaluate the geological conditions.

During deposition the canister with waste will be transported into a shielded transportation canister. At the repository level the canister is transferred to a special deposition wagon designed to handle the canister and the bentonite blocks. The deposition procedure is described in more detail in Appendix 2.

When the deposition is finished in one tunnel, this deposition tunnel is sealed off by a mixture of sand and bentonite. After the complete deposition is finished all rock openings such as tunnels, shafts and ramp will be sealed off by a mixture of sand and bentonite.

2.3 Medium Long Holes

The Medium Long Holes (MLH) /2-2 / concept constitutes an alternative to the KBS-3 where the storage tunnels with vertical boreholes will be replaced by 1.6 m diameter horizontal deposition tunnels. The principal layout will be fairly similar compared to the KBS-3 concept but deposition of canisters in a small, horizontal tunnel puts forward demand for a very different deposition procedure. The concept is based on the same type of canisters as the KBS-3 concept. A principal layout for the MLH concept is presented in Figure 2-3.

The repository will be located to a depth of about 500 m below ground surface and consist of several parallel deposition drifts with a length of about 250 m. The distance between the drifts will be approx. 25 m. The final layout will be dependent on local geological conditions at the repository level.

The access down to the repository level and the central service area will be fairly similar to the KBS-3 concept. The same construction methods will also apply.

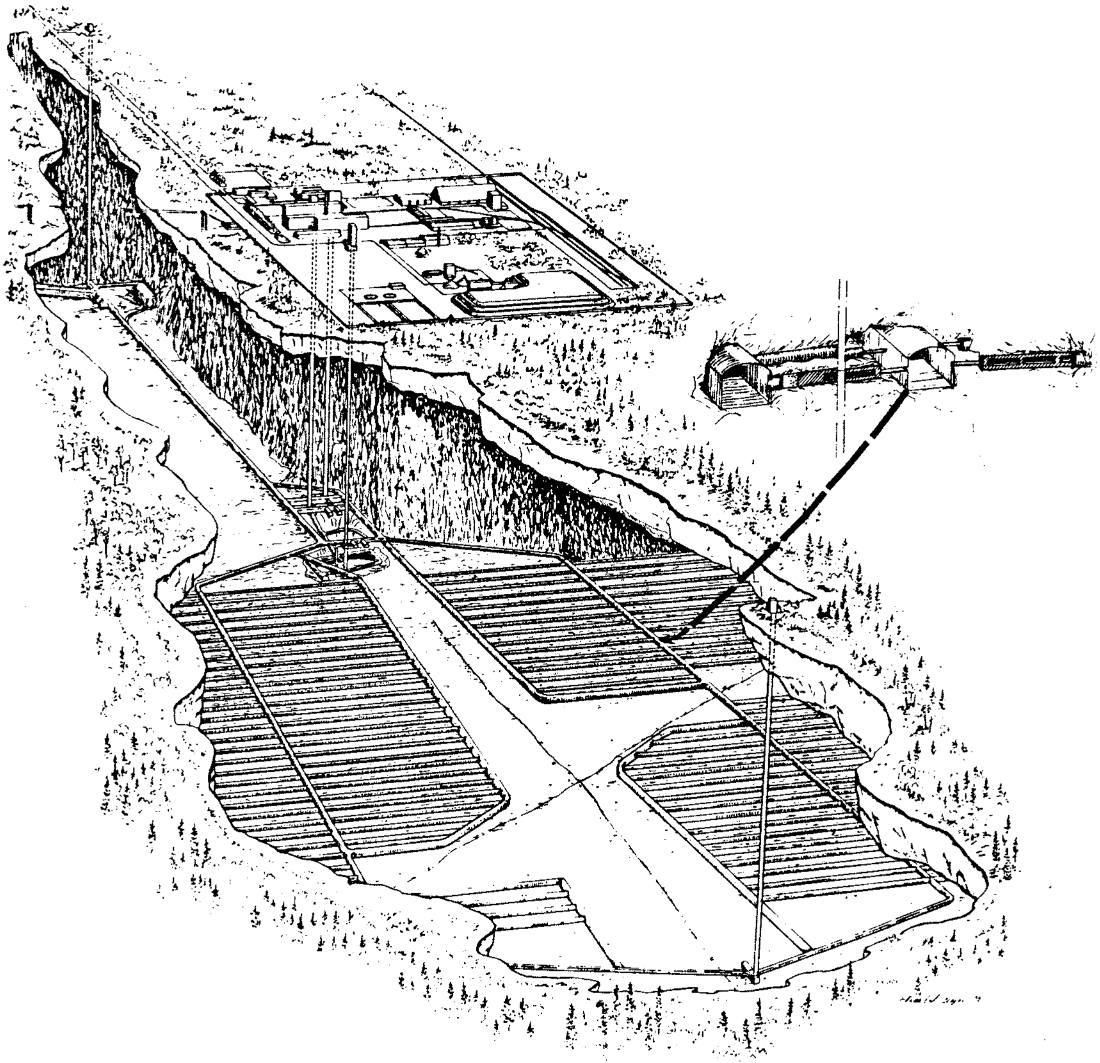


Figure 2-3 Repository according to the MLH principle

The deposition drifts, 1.6 m in diameter, will be constructed by horizontal raiseboring. The boring to final size will be preceded by core drilling and drilling of a pilot hole that will also be used for geological investigations. Two tunnels will be needed for the boring, one back tunnel for assembling of the drilling head and handling of drill cuttings and one for the drilling equipment. It might also be possible to drill these drifts blindly with a modified TBM technique.

The canister will be transported down to the service area in the same way as for the KBS-3 concept. At the service area the canister will be transferred to a special wagon which contains the canister, a cage with bentonite buffer and transport equipment with power unit. The deposition sequence will be divided into two main steps, first deposition of the bentonite cage and secondly pushing off the canister into the central opening of the bentonite barrier. The deposition procedure is illustrated in Figure 2-4.

The bentonite buffer consisting of compacted blocks will be assembled inside a retrievable steel cage. A slotted casing pipe of a bit larger size than the canister is placed on the inside in order to facilitate deposition of the canister. The steel cage will be retrieved and reused. The deposition procedure is described in Appendix 2.

Transportation of the bentonite cage and the canister will be performed by means of a deposition tunnel shuttle with similar design as for the moving part of a tunnel boring machine. The shuttle moves step by step along the tunnel carrying the total load of the bentonite cage and the canister. When reaching the final deposition position the bentonite cage is lowered down onto the tunnel floor. In a next step, the cage is retrieved and the shuttle is moved back to the deposition platform.

The transportation shuttle is then attached to the canister and moved into position close to the bentonite buffer where the canister is pushed into position inside the slotted casing pipe. The deposition is finished by positioning a bentonite plug in the outer end of the hole for the canister.

When the deposition of canisters is finished, the deposition drifts is plugged and the repository is sealed off with the same methods as for the KBS-3 concept.

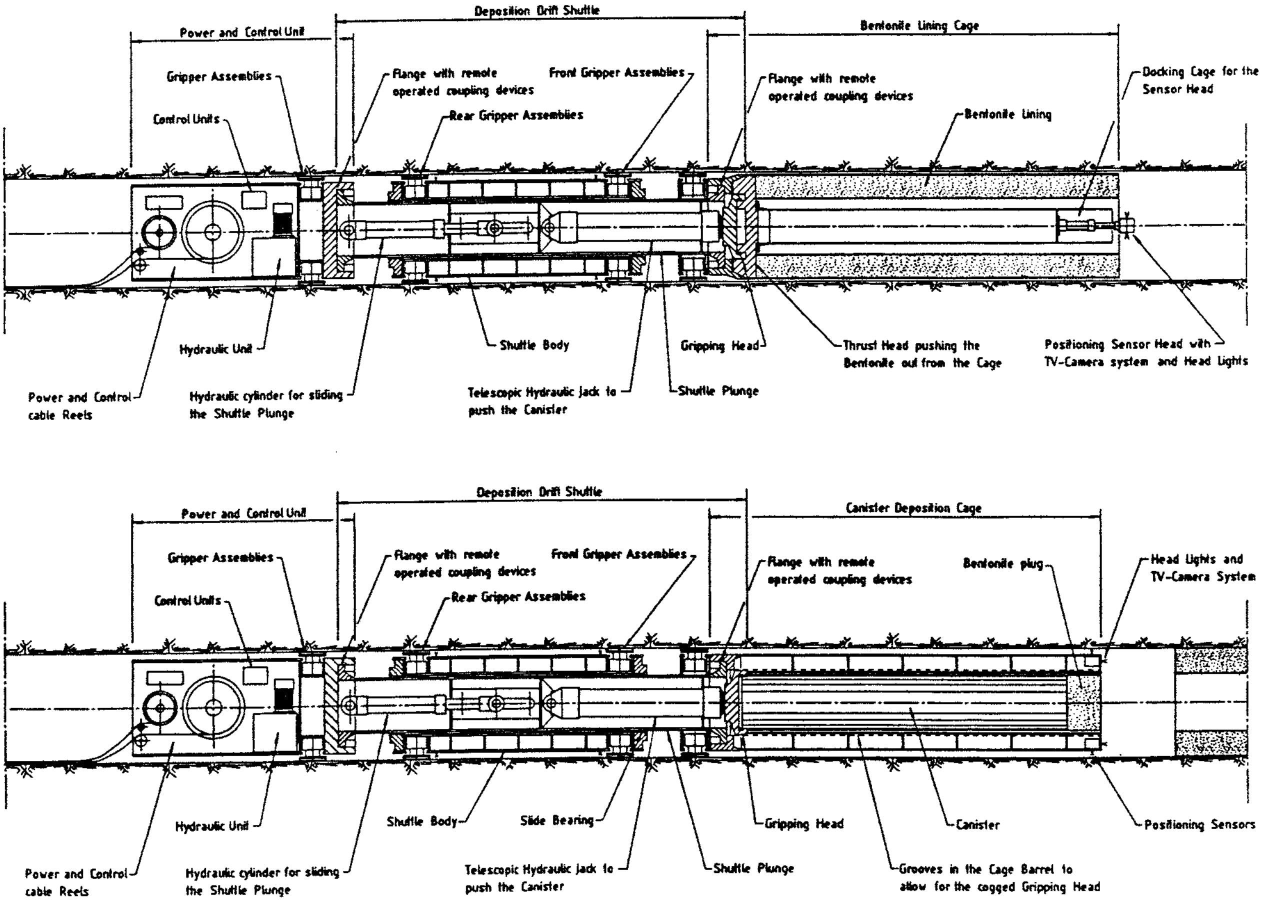
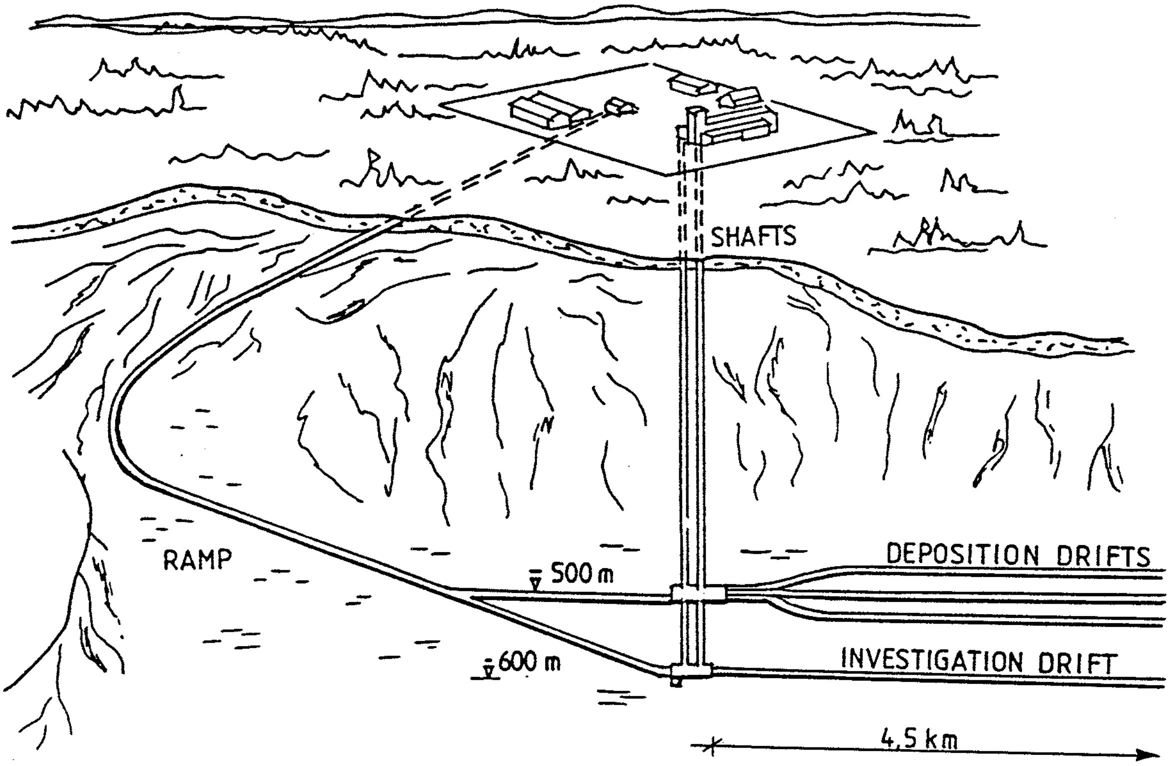


Figure 2-4 Deposition technique for the MLH concept

2.4 Very Long Holes, VLH

A repository design according to the Very Long Holes (VLH) /2-3/ concept consists of three, 4.5 km long deposition tunnels 100 m apart at a depth of about 500 m, see Figur 2.4-1. The long tunnels with a diameter of 2.4 m will contain canisters with spent fuel with a diameter of 1.6 m placed in horizontal position one after another. The repository layout includes an investigation tunnel below the deposition tunnels at a depth of about 600 m. The final direction of the deposition tunnels will be based on among others geological investigations carried out from the investigation tunnel. The investigation tunnel could also be used for inspections during any required space of time after final sealing of the repository.



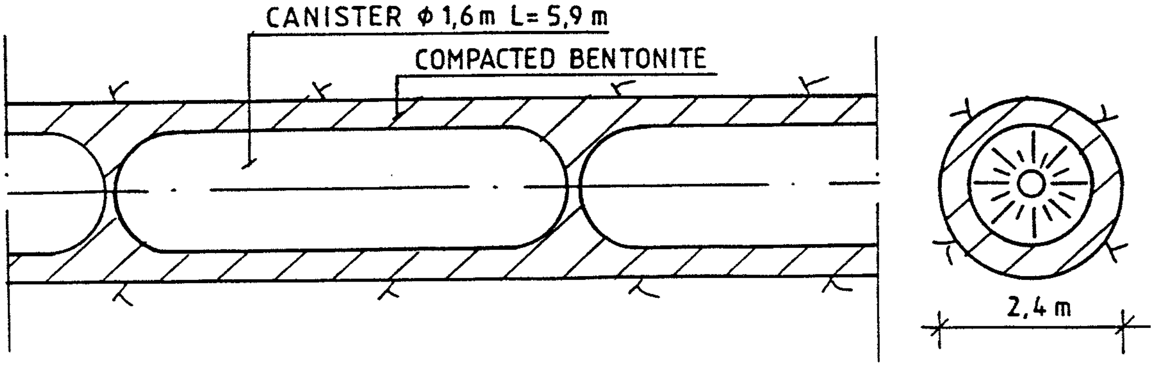


Figure 2-5 General view of a VLH repository

The same geological considerations as for the KBS-3 and MLH concepts will be applicable. With the flexibility gained with the long tunnel system, it should be possible to avoid troublesome zones and to locate the repository tunnels to favourable geological conditions. If a major fault zone would be crossed, the long tunnels could be extended into more suitable geological setting.

Any required part of the tunnel on both sides of fracture zones will be sealed off and not used for storage of radioactive waste.

The access down to the repository will consist of the same type of ramp and vertical shafts as for the KBS-3 and MLH concepts. The investigation tunnel will be an extension of the ramp.

Tunnelling at the repository level will be carried out by TBM boring. Several advantages are achieved with circular tunnels constructed by TBM technique such as less disturbance of the nearfield rock and a more stable tunnel section.

The canister will be contained into a transport shield and transported down to the repository level by for example the RHS train developed by the Swedish contractor Kraftbyggarna AB. In the service area the canister will be transferred to a special wagon designed for transportation in a small circular tunnel. Due to the large size of the canister and limited space in the deposition tunnel, the transportation must be carried out without any radiation protection.

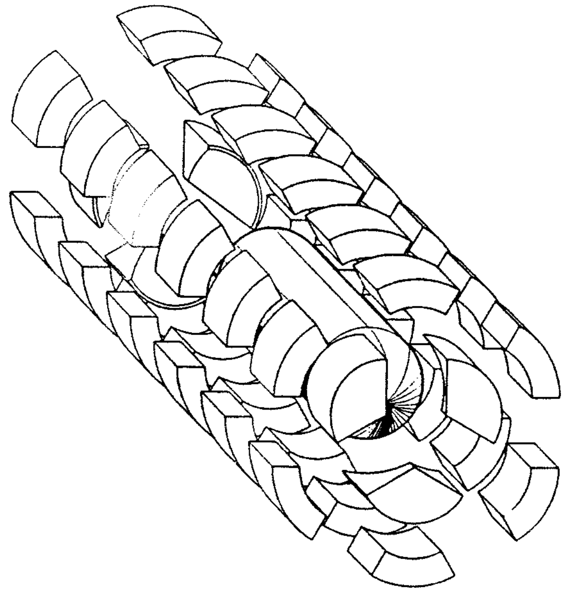
The deposition will start with placing a bentonite bed in the bottom of the tunnels. In a second step the canister is placed on the bed and is in a third step covered with bentonite. The proposed deposition procedure is described in Appendix 2 and is illustrated in Figure 2-6. During longer furloughs in the deposition it might be necessary to place a plug (different systems are possible), permanently or temporarily, close to the last deposited canister.

The 0.4 m thick bentonite barrier around the canisters will consist of saturated bentonite blocks. After homogenization, the average hydraulic conductivity will be in the range of 10^{-12} m/s depending on the ground water quality.

After deposition of the waste canisters the access ramp, shafts and other rock caverns will be sealed off by a mixture of sand and bentonite.

From the beginning the concept was designed for an off-shore location but the same principle is valid also for an on-shore location.

Besides a repository consisting of three long tunnels it is also possible to design a compact repository with drilled 2.4 m diameter tunnels in a pattern similar to the KBS-3 and MLH concepts.



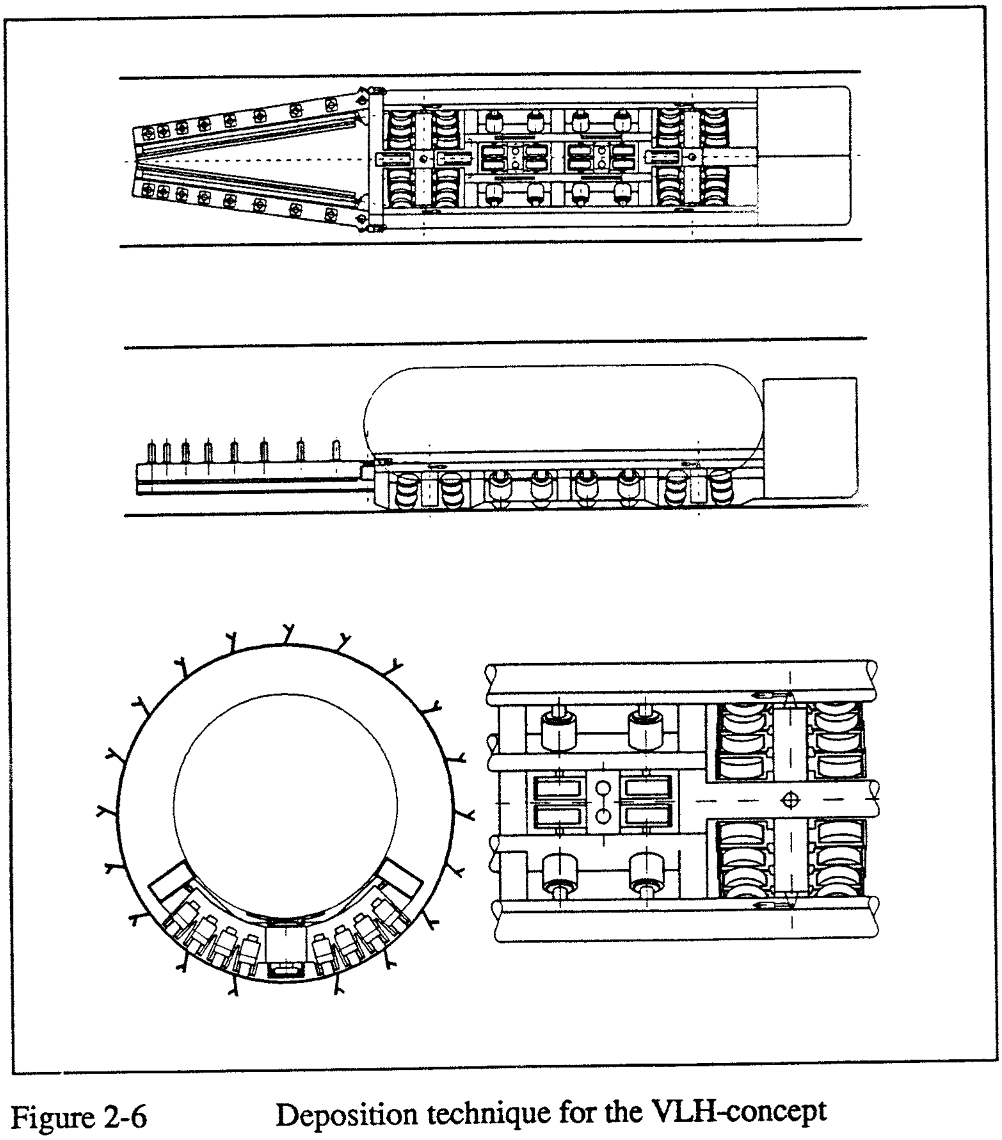


Figure 2-6 Deposition technique for the VLH-concept

2.4 Very Deep Holes, VDH

The basic principle of the Very Deep Holes (VDH) /2-4/ concept is to place the waste at such great depth that the time for migration of radionuclides to the biosphere becomes so long that adequate decay has occurred to eliminate any safety hazard. Besides a thick rock cover above the repository the possible existence of a salt gradient at depth and/or several sub-horizontal fracture zones above the repository might also prohibit transport of radionuclides to the ground surface.

A VDH repository consists of approx. 38 large diameter boreholes drilled to a depth of about 4.000 m, see Figure 2-7. Deposition of waste is planned to be carried out in the section between 2 and 4 km. The boreholes will be located with a respect distance to each other of about 500 m. The final location of each individual borehole will depend on the prevailing geological conditions and prerequisites at ground surface.

The spent fuel is suggested to be contained in concrete filled titanium canisters with an outer diameter of 500 mm and a length of 4.8 m.

The concept is based on oil well drilling technique and experience gained from deep boreholes in crystalline rock such as the Gravberg borehole. The drilling will be carried out by rotary drilling and a light bentonite mud in two steps. First a 1.400 mm (56 in) hole down to 2.000 m and secondly a 800 mm (32 in) hole down to 4.000 m. The boreholes will be secured by a 1.000 mm slotted casing down to 2.000 m and a 600 mm slotted liner with a high void ratio down to 4.000 m. In order to eliminate gas generation the casing and liner is anticipated to be constructed by a non-reactive material such as titanium or copper. Cementing will probably be required locally during drilling for rock stabilization.

During deposition, canisters will be lowered down to the requested position by the drill string. The positioning of the canister will be preceded by placement of a very dense bentonite fluid over an interval of about 10 m above the previously installed canister. The density will be based on the possibility for the canister to enter through the mud and the strength of the canister. Control of canister position during deposition is important and should be possible with technology available in the oil industry. The deposition speed will be dependent on the friction between the canister and the borehole wall/lining.

In order to achieve a sufficient seal the canisters are installed together with blocks of compacted bentonite. The sealing function is based on the prerequisite that the bentonite around the canister should be homogenized and totally fill up the space between the canister and borehole wall. After homogenization the average hydraulic conductivity will be in the range of 10^{-10} m/s depending on the borehole configuration (final size of the boreholes) and ground water quality. This conductivity is sufficiently low for making diffusion the dominant transport mechanism.

The upper part of the borehole will be sealed off by compacted bentonite. The top seal is sugges-ted to consist of asphalt with a concrete plug at the very top.

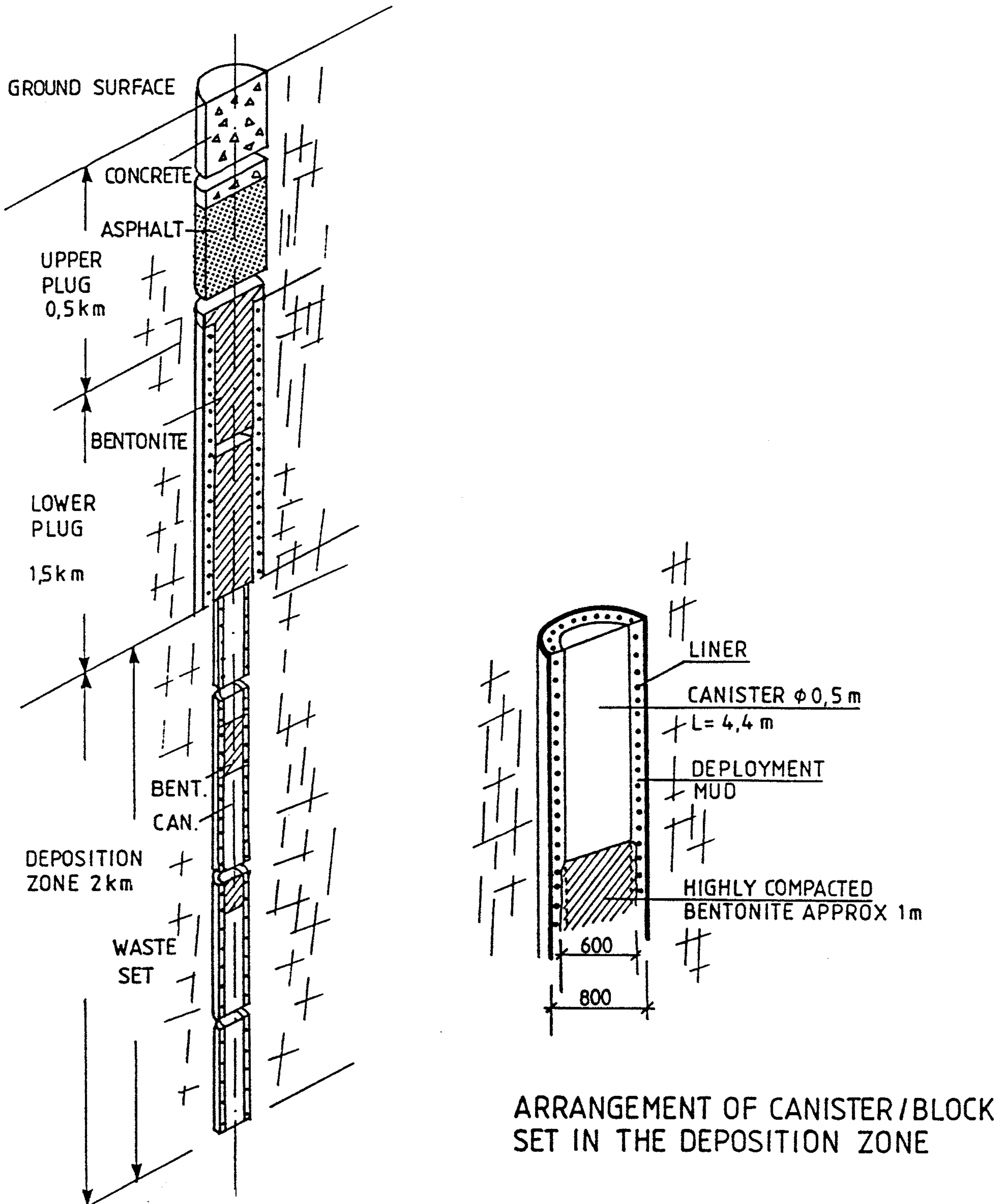


Figure 2-7 General view of a VDH repository borehole

3 METHOD FOR COMPARISON

3.1 General

The Technical Comparison of the repository concepts has been carried out in two phases:

Phase 1

In order to make the comparison and ranking of concepts, essential characteristics and attributes were identified and ordered in a hierarchic structure of the different concepts. The comparison was carried out by one investigator (H Sandstedt) and the result was presented as pros or cons for the concepts. It was not possible, though, to make a final ranking of the concepts based on this analysis as different pros or cons have different importance for the final objective, the choice of the most preferable repository concept. As a result of this first phase it was concluded that the ranking should be carried out by an independent expert group and a method that makes it possible to evaluate the importance of different essential characteristics and attributes. The proposed hierarchic structure for comparison was used as a base for phase 2.

Phase 2 was preceded by a literature search with the objective to identify a suitable decision analysis method for ranking of the four repository concepts.

Phase 2

During this phase, the comparison was carried out by expert judgements. The expert group consisted of six experts, four with connection to SKB and two with connection to TVO from Finland. In a first step the hierarchic structure was reviewed individually by the experts and revised accordingly. The ranking was decided to be carried out according to the method Analytical Hierarchy Process (AHP) /3-1/, which is based on pairwise comparison of criteria. The criteria are ordered in a hierarchy and by the evaluation process a measure is obtained of the relative importance of each criterion.

From the beginning the plan was to test the method with a relatively small expert group and based on gained experience performe a ranking exercise also in a larger group. However, due to the very pronounced result with the small group (see chapter 8 Result) no further group judgements was carried through.

3.2 Choice of method for comparison

In order to locate and choose a suitable method for comparison and ranking of the the repository concepts, a literature search was conducted. Several principles are available for making decisions among discrete alternatives with multiple decision criteria. Three main groups could be distinguished:

- Multiattributive utility decision making:

  The expected utility of each alternative is calculated and the alternative with the greatest utility is chosen. The calculation of utility is extremely difficult when there are many attributes.

- Sequential elimination principles, Lexicographic ordering:

  Attributes are ordered in terms of importance. Then the alternatives are compared with regard to the most important attribute. If one single alternative ranks the highest, then that alternative is chosen. If not, one moves down to the second most important attribute, compares alternatives with regard to that attribute and so on until a single winner can be chosen .

- Weighting principles:

  There exist several weighting principles, see Saaty /3-1/.

As criteria for comparison were of both quantitative and qualitative types, a ranking method was preferable. As a result ot the literature search the Analytic Hierarcic Process (AHP) develpoed by Saaty /3-1/ was chosen as ranking and evaluation method for the comparison. The choice of AHP was based on the following charateristics of the problem of ranking repository concepts:

- Multiattributive-There were several attributes to be compared simultaneously
- Hierarchic-Some attributes were composed of several lower level attributes
- Subjective ranking-Almost all comparisons had to be based on expert judgement
- Group decision-A panel of experts was to be used for the ranking

These characteristics, plus the fact that the AHP is established and proven and that there is software available for the evaluation led to this choice of method.

4 ANALYTICAL HIERARCHY PROCESS (AHP)

4.1 Main features of the AHP

The main features of the AHP /4-1/ method are :

- Hierarchic structuring of problem
- Pairwise comparison

Hierarchic structuring

The first step in using AHP is to structure the problem in a hierarchy with the ultimate goal at the top and with one or more levels of criteria below. The graphic structure will be that of an inverted tree, with the goal as the root at the top and the branches going down until one reaches the leaves, the different alternatives to be compared at the bottom. The principle of a hierarchic structure is illustrated in Figure 4-1.

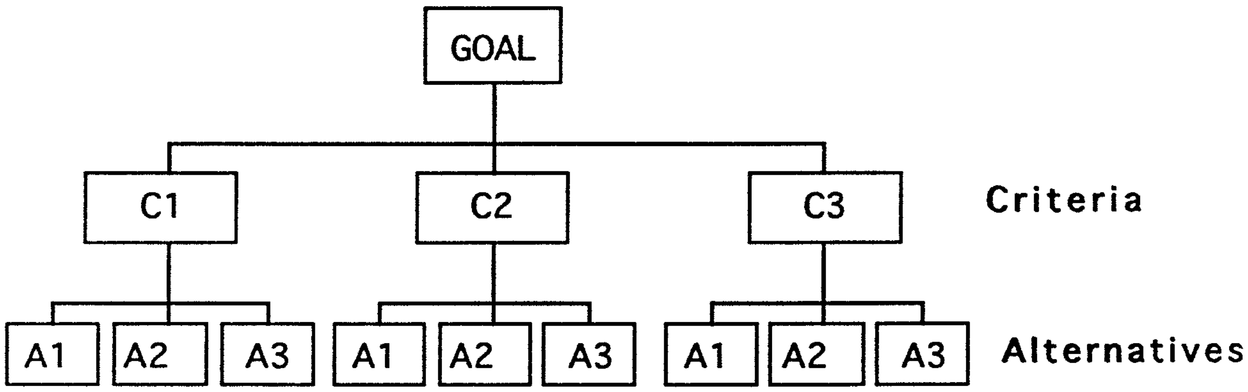


Figure 4-1 Principle of the hierarchic structure

The structure can be expanded. So can for instance different scenarios and/or different actors be added. Although these possibilities were not used in the present study, they can be used in an extended study.

Adding a level for different experts that take part in the ranking can be useful when their expertise is in special fields. This will be discussed later as one method for use in group decisions.

One important feature is that the participants in the ranking process are involved in the design of the hierarchic structure.

Pairwise comparison

A very important feature of the AHP is that all comparisons between criteria and between alternatives are made pairwise and that they are made with regard to a criterion on the next higher level. In this way it is possible to give correct judgements even in the case where lots of criteria obscure the goal.

In the simple case above (Figure 4-1) the following comparisons will be made:

- First the importance of the criteria with regard to the goal:

  C1 is compared to C2 with regard to the goal
  C2 is compared to C3 with regard to the goal
  C1 is compared to C3 with regard to the goal

- Then the alternatives with regard to the criteria in the level above:

  A1 is compared to A2 with regard to the criterion C1
  A2 is compared to A3 with regard to the criterion C1
  A1 is compared to A3 with regard to the criterion C1
  This is repeated with regard to the other two criteria

The importance attached to a criterion or an alternative can be expressed by the use of different measures:

- If there is an absolute measure like cost, that can be calculated for the alternatives, then the cost expressed in monetary units can be used for comparing alternatives with regard to the criterion cost
- For scenarios one can use the likelihood of the occurrence of that scenario stated as a subjective probability
- For the common pairwise comparisons, it is necessary to have the expert judgements expressed on a suitable scale

Such a scale has been developed for use by the AHP and has been presented in literature, see for instance Saaty /4-1/. The scale is verbally based with an interpretation into a numerical ratio scale, see Table 4-1 below. As can be seen, the scale ranges from 1 to 9. This scale has been chosen as being suitable from psychological reasons as being a "natural" scale that can be surveyed.

Table 4-1 Pairwise comparison scale (Saaty 1990)

Numerical scale	Verbal scale	Explanation
1.0	Equal importance of both criteria	Two criteria contribute equally to
3.0	Moderate importance of one criterion over another	Experience and judgement slightly favour one criterion over another.
5.0	Strong importance of one criterion over another	Experience and judgement strongly favour one criterion
7.0	Very strong importance of one criterion over another.	An criterion is strongly favoured and its dominance is demonstrated in practice.
9.0	Extreme importance of one criterion over another	The evidence favouring one criterion is of the highest possible order of affirmation

2.0; 4.0; 6.0; 8.0	Intermediate values between two adjacent judgements	Compromise is needed between two judgements

In practical work the elements that are to be compared to each other are arranged in a (square) matrix as below.

Table 4-2 Example of ranking matrix

	Alternative 1	Alternative 2	Alternative 3
Alternative 1 .	1	3	5
Alternative 2 .	*1/3*	1	1/3
Alternative 3 .	*1/5*	*3*	1

By convention, the judgements are entered with the elements in the left-hand column being the first element in the comparison with the elements in the top row. For instance:

Comparing alternative 1 with alternative 2 the following judgement is given;
"Alternative 1 is moderately more important than alternative 2" hence the figure 3 is entered in the matrix. All elements on the diagonal are 1 as one cannot prefer one element to itself.
For reverse comparisons, the reciprocal of the scale number is used, i.e $c_{ij} = 1/c_{ji}$
In the comparison between alternative 2 and alternative 3, the latter alternative is preferred. Because of this the reciprocal number of the judgement is entered in the matrix.

Remark: Only the top half of the matrix is filled in during the comparison. The other positions are filled in automatically.

4.3 Evaluation.

The result of the evaluation is a set of weights which give the overall importance of the different alternatives with regard to the goal. One can also calculate the relative importance of the criteria relative to the goal and the importance of the alternatives relative to the criteria.Generally, one can have the importance of one set of elements either relative to the goal (global priorities) or relative to the next higher level in the tree (local priorities)

The mathematics of the evaluation process is presented in Appendix 1.

Inconsistency

When making the pairwise comparisons it is easy to contradict oneself:
One might state that one prefers apples to pears and pears to bananas. Logically one should then prefer apples to bananas but one might put down in the comparison that one does in fact prefer bananas to apples.There are methods to spot and measure such contradictions or inconsistencies.

One can calculate the so called consistency index (C.I) and also the consistency ratio (C.R). The consistency ratio is the ratio of the actual consistency index to the consistency index one would get by filling in random values for judgement. A value less than 0.1 is considered acceptable. If higher values are received the ranking should be further analysed.

Group decision methodology

When there is not just one expert, but a group of people that are to give their judgements there are several possible methods that can be used which are discussed below.

Judgement given as a group

If the group works physically together and can agree on the judgments, one has consensus and the weights can be calculated as if they were from a single person. There are some drawbacks though with group decisions:

- One person can by force of a strong personality dominate the meeting
- People might have interest only in certain aspects of the problem and might try to "trade their votes" on other aspects

If spontaneous consensus cannot be reached, it might be possible to calculate the (geometric) mean of the individual judgements and see if consensus can be reached on that.

Judgement given individually

In this case the drawbacks discussed above are avoided, but it might be difficult to amalgate the results and to draw conclusions. It is important that the participants feel involved and that they are given the possibility to influence in the design of the hierarchy. The judging can be done by mail, but should be preceded by a discussion of the problem, the AHP structure and the meaning of the criteria for comparison.

Expertise

A problem common to both approaches is the degree of expertise that different members possess on different parts of the problem. In a group decision the group can often take notice of this when discussing towards a consensus.

In individual judgement the problem is more difficult and one might have to add an extra level in the hierarchic structure where it is possible to give figures representing the individual expertise relative to different areas.

Evaluation

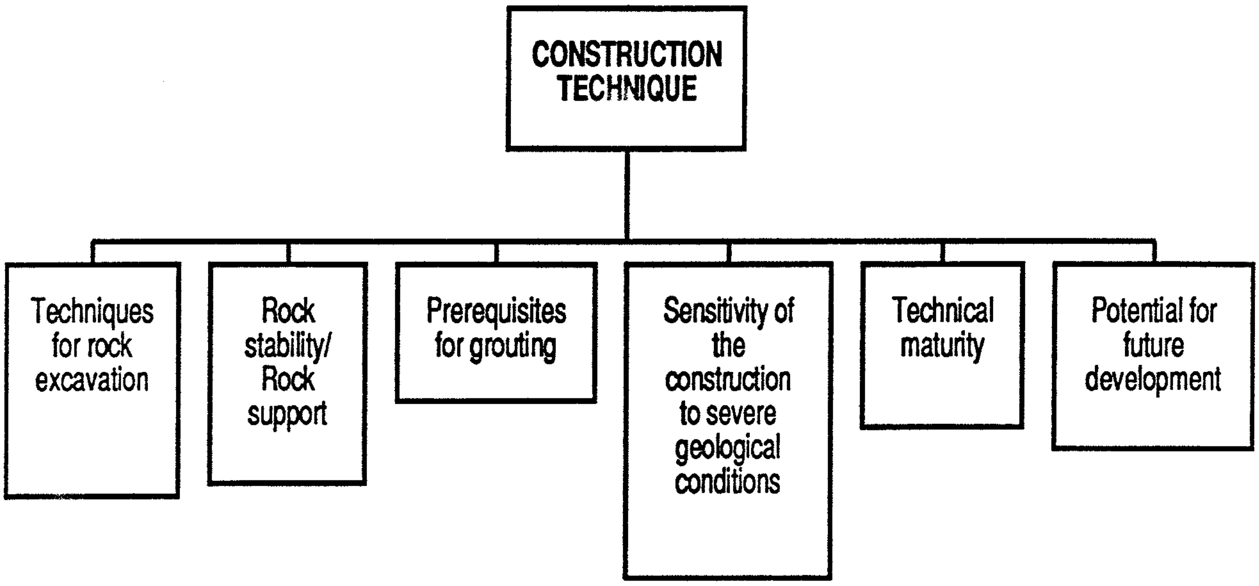
In this study, the commercial software Expert Choice™ /4-2/ that runs on IBM-compatible personal computers has been used for the evaluation. The evaluation process is described in Appendix 1.

5 RANKING PROCEDURE

The ranking process was carried out in the following steps:

- Selection of expert panel
- Review of repository concepts in order to eliminate factors in the ranking related to different prerequisites
- Interviews with the members of the expert group with the objective to discuss criteria for comparison
- Design of a hierarchic structure for comparison
- Individual expert ranking
- Evaluation
- Group discussion about the result with the experts

All experts taking part in the judgement procedure were participating in the design of the hierarchic structure. It was considered satisfactory to carry out the pairwise comparison individually on forms sent out by mail. The hierarchic structure together with the different levels that has been used in the ranking is presented in Figure 7-1. A set of questionnaires formed the basis for the experts. They consisted of a short description of the criteria for judgement and of the AHP technique plus a set of forms to be filled in. Each form showed parts of the model structure and had a matrix in which the judgents were to be written down. An example is presented in figure 5-1.



CONSTRUCTION TECHNIQUE	Excavation	Stability	Grouting	Sensitivity	Maturity	Development
Excavation	1					
Stability		1				
Grouting			1			
Sensitivity				1		
Maturity					1	
Development						1

Figure 5-1 Example of forms to be filled in by the experts

6 SELECTION OF EXPERT PANEL

6.1 General

The choice of expert panel is important and several aspects were considered which are dicussed below:

Independence

If several experts cast the same views this fact should carry a large weight. This weight is lessened, however, if the experts are not independent of each other (in a statistical sense). The reason of such dependence could be factors such as common education, work in the same projects, study of the same literature etc. Dependency between experts might in its extreme form reduce the value of a group to that of a single expert.

Dependency among the experts participating in this ranking has been evaluated and it was shown that the experts were independent of each other in a statistical sense, see chapter 9.

Expertise

The panel of experts will be asked to give their opinion on questions in different fields. Naturally it will be almost impossible to find a group of experts where everybody is a true expert in all fields that will be discussed. This means that the group of experts will consist of people that are experts in one field, knowledgeable in adjoining fields and laymen in the rest. One method to overcome this problem is to assign weights for each expert to different fields. This approach might be difficult and one might therefore replace it by a dichotomy; Either you are an expert in the particular field (weight =1) or you are not (weight= 0). In PASS, however, each expert was given the same weight for all fields..

Creativity and openmindedness

The work of finding relevant criteria for comparison will be an interactive process with the expert group involved. It will therefore be necessary that the panel consists of individuals who have such basic knowledge of the concepts that they can actively participate in the process.

Involvement

When working with an expert group it is important for the final result to engage the experts early in the ranking procedure.

6.2 Choice of experts for the ranking

For the PASS ranking it was decided to use a smaller expert group with people who had been involved in questions related to concepts for deposition of spent nuclear fuel for a long time. The ambition was that each member would be an expert in some fields and more of a generalist but knowledgeable in others.

Below is a short presentation of the appointed expert group:

- Lars Ageskog, M.Sc Civil Engineering. L Ageskog is employed by the consultant company VBB VIAK and has been working with design and construction of civil engineering structures for nuclear power plants and sub-surface facilities. He has participated in the design work of all the four analysed concepts.
- Anders Bergström, M.Sc. Civil Engineering. A Bergström is a retired employee from SKB with former responsibility for technical development of the repository concepts.
- Tapani Kukkola, M.Sc. Mechanical Engineering. T Kukkola, employed by the Finnish power company Imatran Voima OY has been working with design of nuclear powerplants and as consultant to TVO concerning facilities for deposition of nuclear waste.
- Roland Pusch, Prof. Geotechnics. R Pusch is president of the company Clay Technology AB and is an expert in issues related to the buffer material bentonite and is also working with R&D concerning rock mechanics and grouting.
- Reijo Riekkola, M.Sc. Civil Engineering. R Riekkola is president of the consultant company Saanio & Riekkola and is working extensively with design of sub-surface facilities. R Riekkola has been involved in several projects concerning deposition of nuclear waste in Finland.
- Claes Thegerström, M.Sc. Eng. Physics. C Thegerström is employed by SKB and is now Director of Public Affairs and Siting. C Thegerström participated in the development work for different repository concepts and has also been working as project manager for OECD/NEA in Paris.

7 CRITERIA FOR COMPARISON

In order to review proposed criteria for comparison individual interviews were carried out with each member of the expert group. As a result of the interviews and discussions with the PASS project group a model was suggested where the hierarchic structure has been separated into:

- **Feasibility**
- **Construction**
- **Operation**
- **Human intrusion (Post-closure)**

The final hierarchic structure that was used in the ranking is presented in Figure 7-1. Descriptions and explanations of the different criteria for comparison are presented in Appendix 2. The outcome of the interviews with the expert group has been documented. Below is a short summary of the most important points of view.

The proposed ranking method was new to all experts except T Kukkola who earlier had been involved in the ranking of two different nuclear power plant concepts in Russia with the AHP method. This experience emphasized how important it is for the outcome of the result that the ranking is very well prepared and that the experts work close to the decision making organisation. Also important is that the criteria for comparison are independent of each other.

A general view among the experts was that ordering of the comparison in a hierarchic structure provides a comprehensive overview of all factors that influence the ranking and the preference of repository concept. Some difficulties were also foreseen and the following could be mentioned among others:

- The technical maturity of certain systems, details etc sometimes differs between the concepts. In some cases the task is also to compare proven technology with unproven

- The function of the repository should also be included in the comparison. The experts are to analyse all parts of the comparison in the short time available for the ranking process which might be difficult

- A distinction between technology, economy and long term safety is desirable, although the distinction is not always clear

- Robust systems are normally prefered. In some cases expected values versus statistical distributions around these values have to be compared

- Requested geological conditions for a repository need to be settled as a prerequisite for the comparison

Viewpoints by the experts on proposed criteria for comparison have been an important input to the final decision of a hierarchic structure for comparison. Some experts were of the opinion that the criterion post-closure should also include factors related to the long term safety function of the repository and adjustability to the prevailing geology. This latter criterion is to some extent included in the safety analysis of the repository concepts that is presented in a separate SKB report /7-1/.

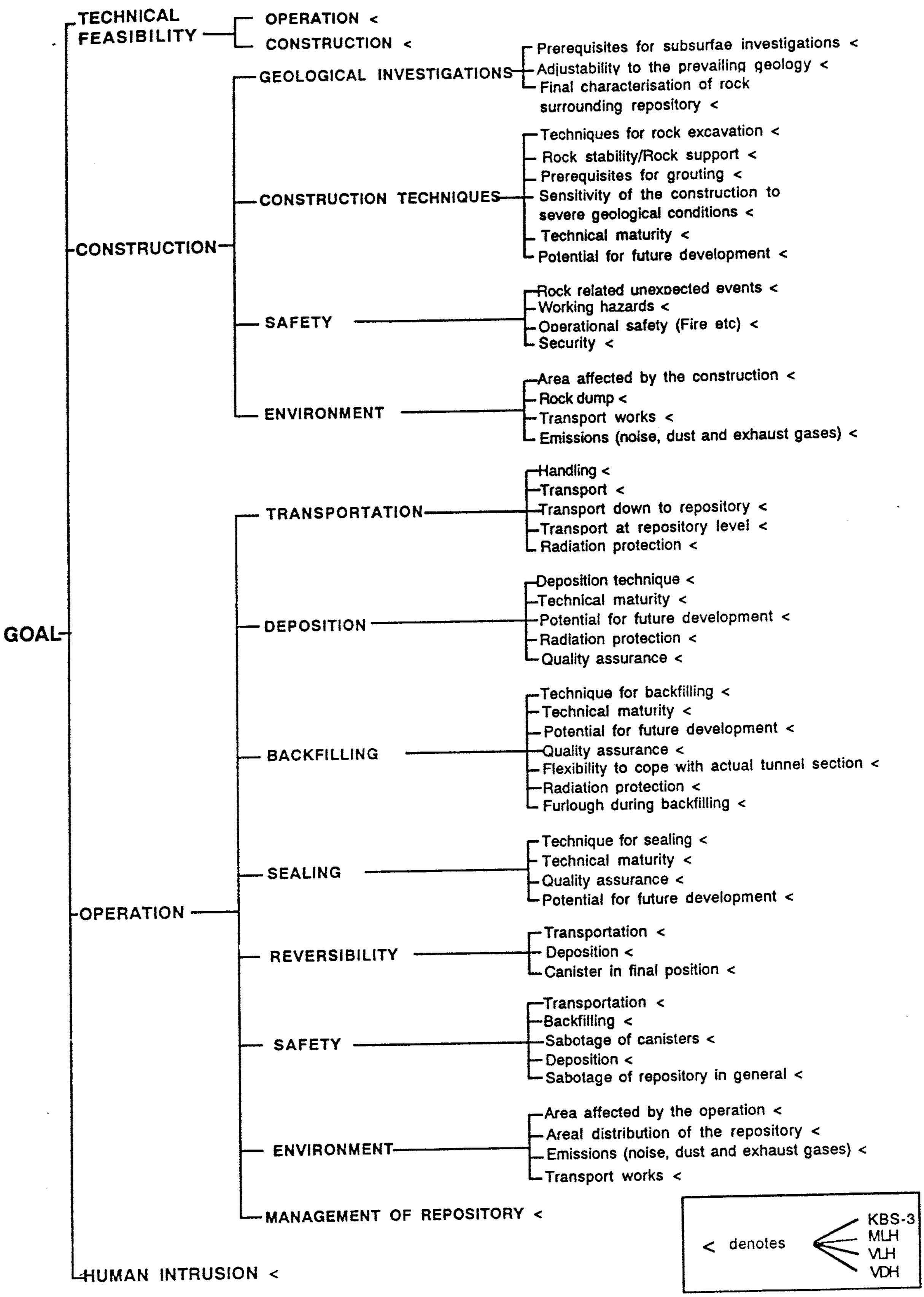


Figure 7-1 Hierarchic structure for comparison

8 Results

The result of the ranking is presented both as group means and as individual values. In the latter case this is done without giving the name of the answering expert which is of minor interest for this comparison.

The different levels in the hierarchic structure is designated as in Figure 7-1. Level 0 is the goal.

Evaluation

In a first evaluation some data were missing in some questionnaires. In this first preliminary evaluation the missing data were replaced with a rough estimate of the means from the other experts combined with a subjective adjustment to cater for the "pattern" of the expert compared with the others.

This material was used as a basis for the preliminary group discussions with the expert group about the result of the ranking. After that meeting the missing data were received from the experts together with some small changes in their original judgements.

As the data were then considered to be final, a renewed calculation of all weights was done.

Results are presented for the different levels, giving the priorities either relative to the goal (global priorities) or relative to the parent at the next higher level (local priorities).

Notice that the local priorities add up to 1 for each parent node.

Statistical measures

The results of the comparison are given with the individual rankings but also with the group mean. In order to have a measure of the spread of the individual answers around the mean the coefficient of variation (CoV) is also given.

The definition of CoV is :

CoV = Standard deviation/Mean i. e a normalized standard deviation. Standard practice is followed thus presenting the CoV as a percentage.

Nothing in literature has been found to indicate what level of CoV is to be expected in this type of group work. In order to graphically illustrate the spread of statistical distribution with different CoV Figure 8-1 has been prepared. In the figure are shown normal distribution with coefficients of variation of 10, 20 and 50 %. This has been done for two different values of the mean (1 and 10) in order to demonstrate the fact that the CoV is a relative measure of the curves spread rather than an absolute measure.

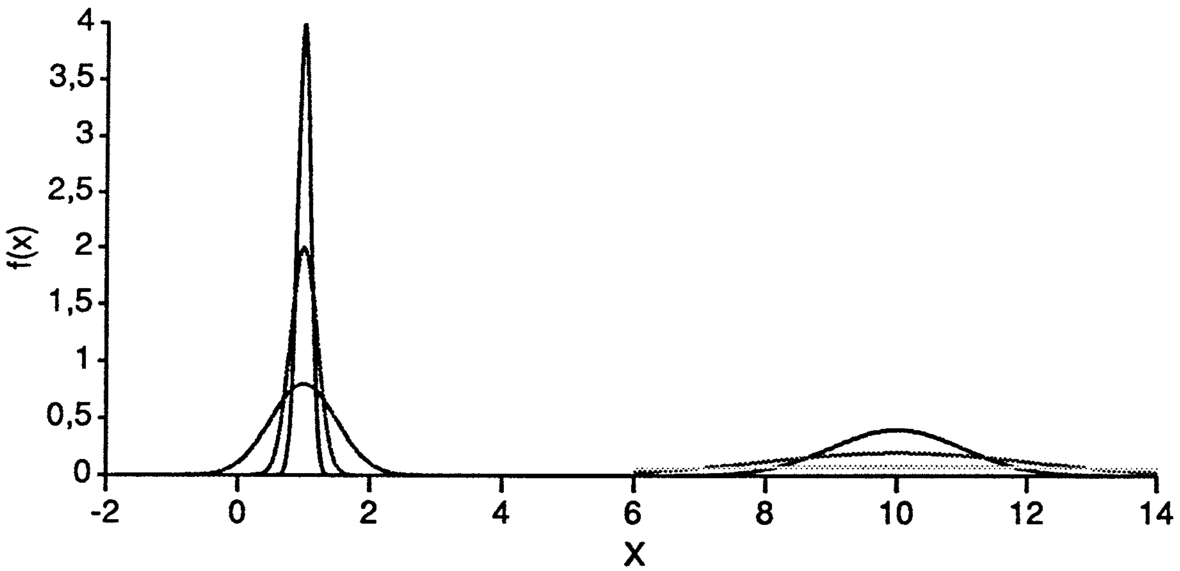


Figure 8-1 Coefficients of variation

Calculated results

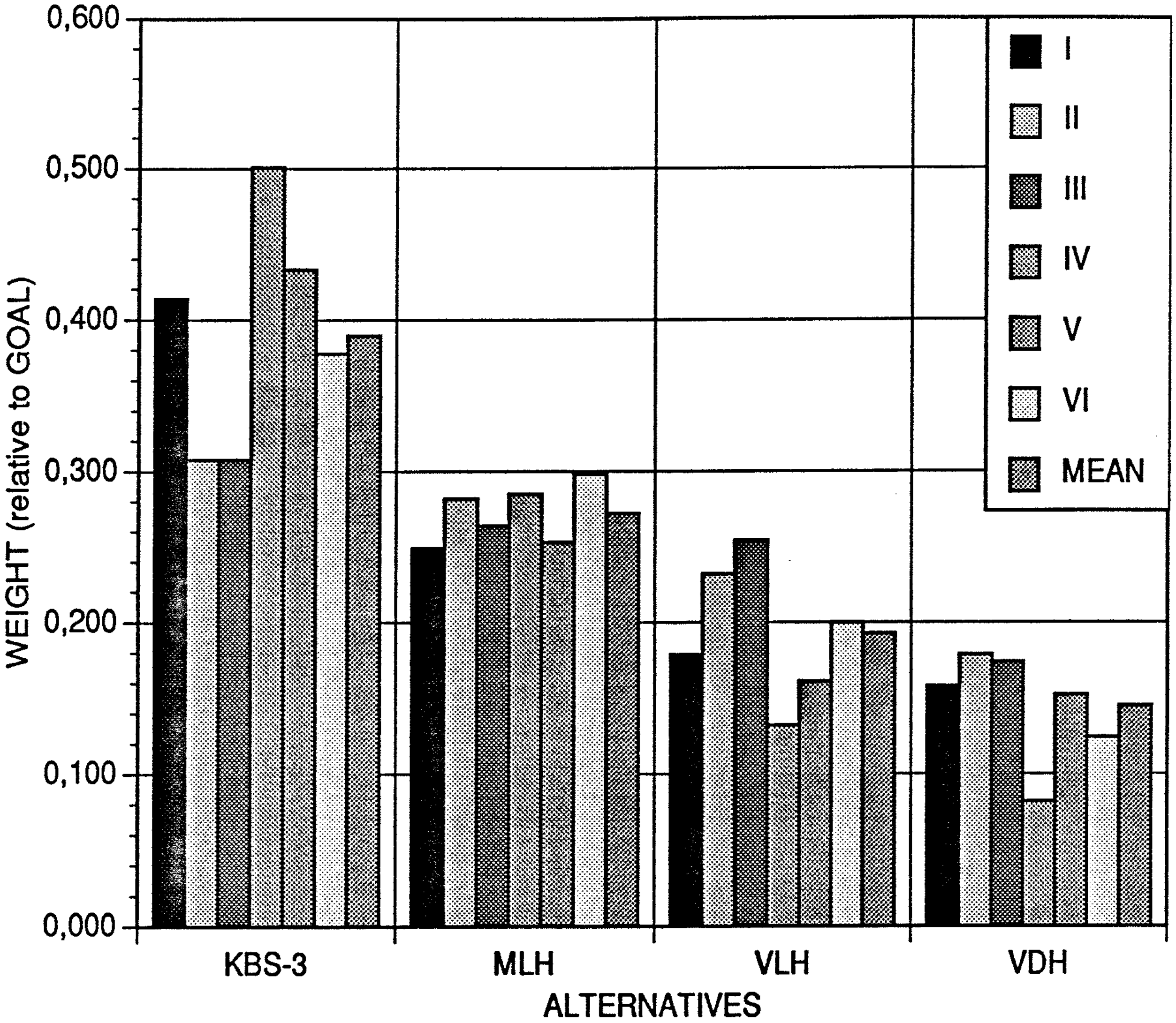
For the first three levels the following results were obtained:

Level 0

Weight of alternatives with respect to goal, are presented in Figure 8-2. As can be seen, all experts ranked the concepts in the following order:

1. **KBS-3**
2. **MLH**
3. **VLH**
4. **VDH**

The CoV is never higher than 25 % with the lowest value for the MLH concept.

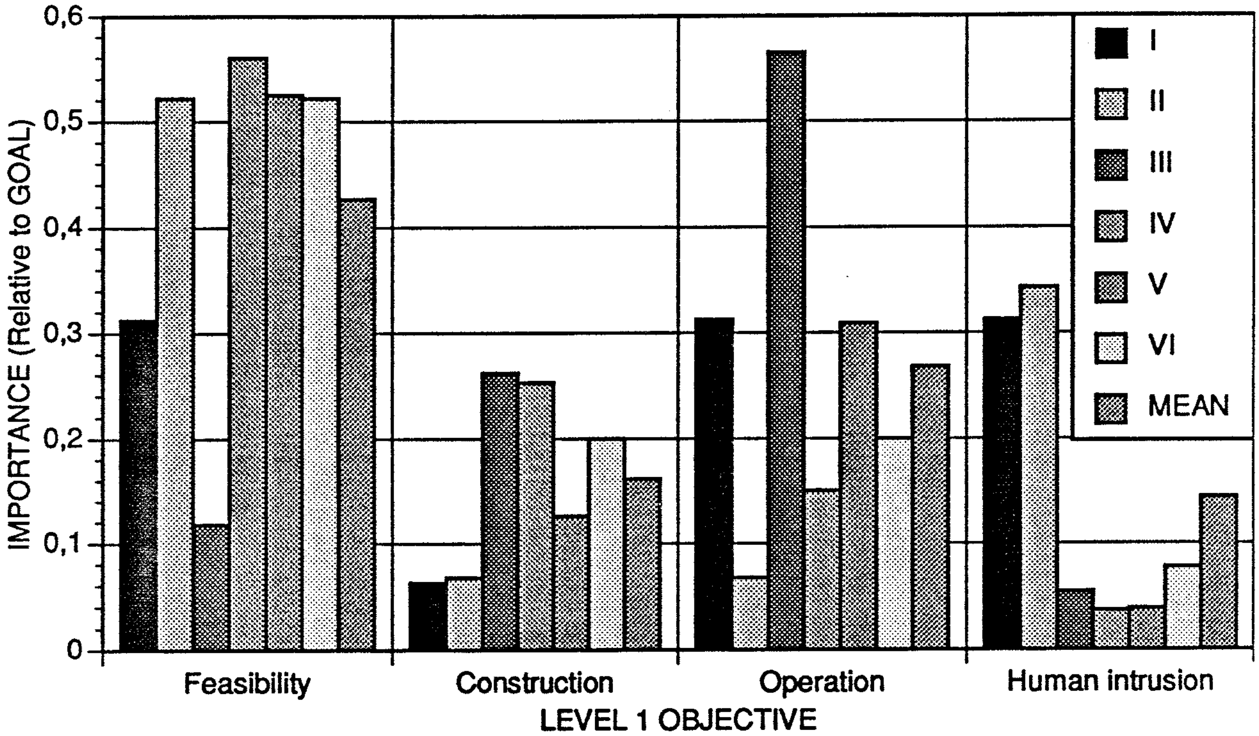


	I	II	III	IV	V	VI	MEAN	CoV (%)
KBS-3	0,414	0,308	0,308	0,501	0,433	0,378	0,390	19
MLH	0,249	0,282	0,264	0,285	0,253	0,298	0,272	7
VLH	0,179	0,232	0,254	0,132	0,161	0,200	0,193	23
VDH	0,158	0,179	0,174	0,082	0,152	0,124	0,145	25

Figure 8-2 Weight of alternatives with respect to main goal

Level 1

In Figure 8-3 the importance of each of the four activities on level 1 is presented.
It is interesting to note that feasibility is ranked the highest with operation as second and construction as third closely followed by human intrusion. The main criterion to fulfil in order to reach the goal is thus feasibility according to the groups opinion. Note, though, that the variations are much higher than for level 0 and that some experts had a different ordering.



	MEAN	CoV (%)
Feasibility	0,427	41
Construction	0,162	55
Operation	0,268	65
Human Intrusion	0,144	100

Figure 8-3 Result of the ranking, weights with respect to level 1

Level 2

In Figure 8-4 is shown the importance of elements on level 2 relative to the goal (i.e. their global importance). As can be seen, the two elements that comprise Feasibility, have the highest priority with the other elements being roughly equal. Variations within the expert group are, however, quite large.

Figure 8-5 shows the weight of the four concepts relative to the objectives to be reached at level 2. As can be seen, the KBS-3 concept is considered to be the one with the greatest potential to obtain the criteria at level 2 except for environmental requirement during operation. For that single criterion both VLH and MLH are ranked higher, the latter only marginally, though. It can also be observed that for all other criteria the ranking order is the same: KBS-3 first followed by MLH,VLH and VDH. The rankings given are the mean value of the experts' individual rankings.

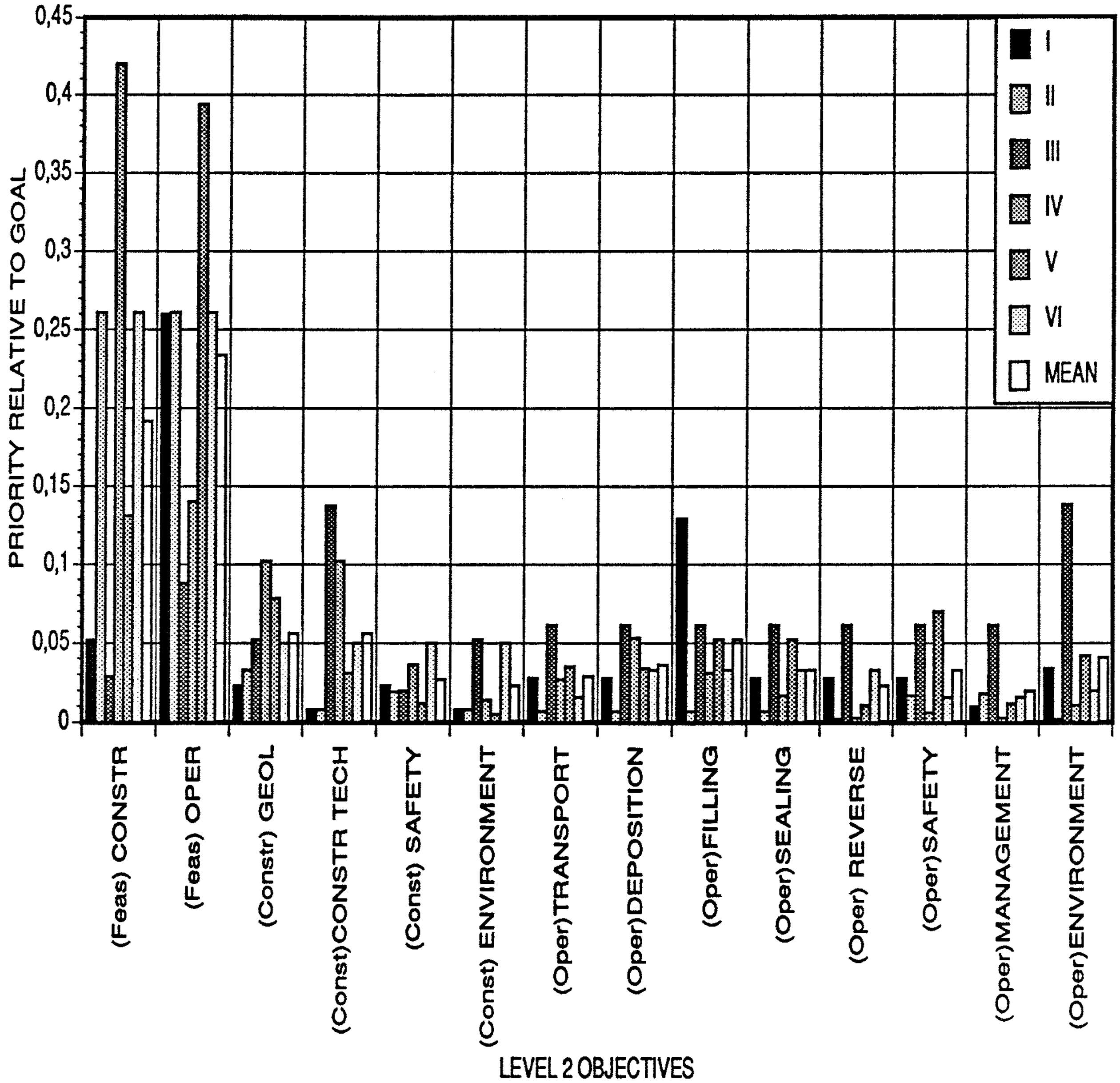


Figure 8-4 Importance of elements on level 2 relative to goal

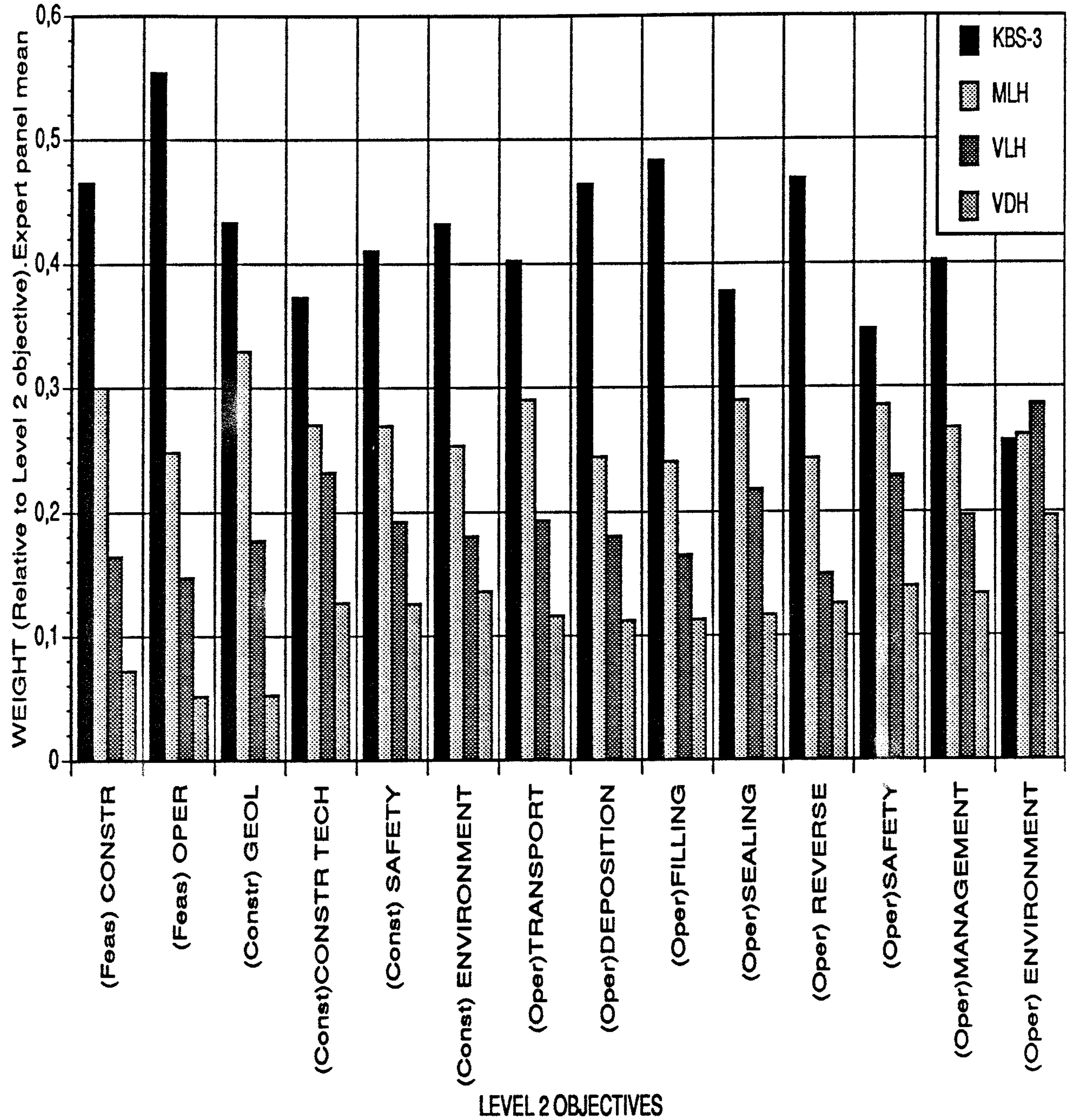


Figure 8-5 Weight of alternatives relative to level 2

9 Robustness of ranking

Before accepting the results of the ranking procedure, one important question must be answered; Is the result of the expert ranking robust? With that question several things can be meant:

- The hierarchic structure model:
  - Is the model itself robust or will a small change lead to a different ranking of the alternatives?
  - Is the result sensitive to small changes in the judgements entered as pair-wise comparisons?

- The experts:
  - Is there a common understanding of the decision criteria?
  - Are the experts representative or is it likely that another group would reach a different ranking?

These questions are of necessity interrelated. The model is for instance dependent on the experts' understanding of the criteria and so on.

The model

The robustness of the model was checked by deleting the level 1 factors of Post-closure (human intrusion) and Feasibility. These two factors were chosen on the grounds of importance and of a slight vagueness of their definitions. The results are shown in figure 9-1.

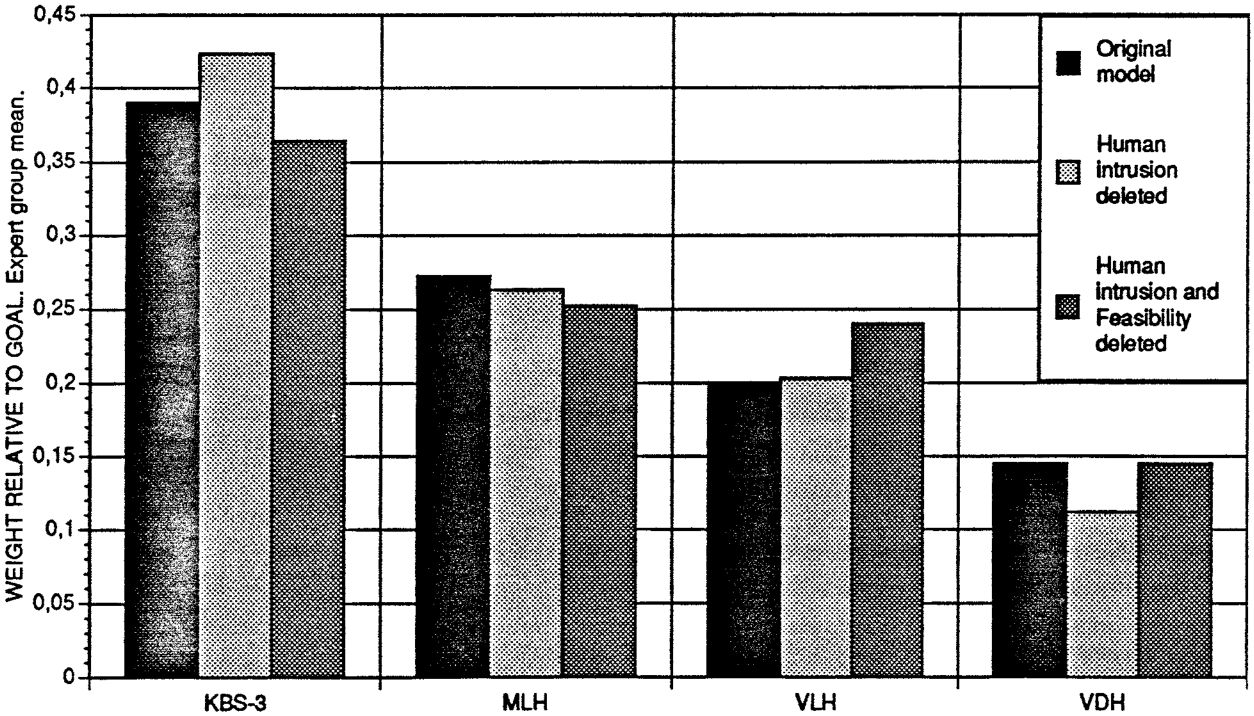


Figure 9-1 Influence of model on final ranking (mean values)

As can be seen, the ranking will not be changed even if such a rather large change is made in the model.

Another observation of the robustness of the model can be made according to the following:

In the preliminary evaluations a preliminary model was used. This model was identical to the final model, except for the fact that during Operation the branch Environment was deleted so that the basic software module would be able to handle the problem. As the data were then considered to be final, a renewed calculation of all weights was done with the aid of the reduced model as well as a complete model. This calculation was done with an auxiliary program to Expert Choice™ /9-1/, "Largemat" that can handle large matrices.

In Table 9-1 below, these two results are compared for each expert with the results from the reduced model marked with an asterisk (*).

Table 9-1 Influence of the model structure

	I	I*	II	II*	III	III*	IV	IV*	V	V*	VI	VI*
KBS-3	0,41	0,42	0,30	0,30	0,30	0,31	0,50	0,50	0,43	0,43	0,37	0,37
MLH	0,24	0,24	0,28	0,28	0,26	0,25	0,28	0,28	0,25	0,25	0,29	0,29
VLH	0,17	0,17	0,23	0,23	0,25	0,23	0,13	0,13	0,16	0,15	0,2	0,2
VDH	0,15	0,16	0,17	0,17	0,17	0,19	0,08	0,07	0,15	0,15	0,12	0,12

As for the question of sensitivity of the result to changes in the judgement, no special tests have been run. As has been noted earlier, some changes and additions of the judgements were made by the experts. The impression of the authors is that such changes usually have a very small influence on the result.

There was one exception, though. When one expert made a radical change at one point in his judgements, his ordering of the alternatives changed to coincide with the others. His change of judgement was caused by a difference in interpretation of the criteria for judgement and this difference was removed at the group meeting with the experts.

As far as these tests and other observations show, the result of the ranking is not sensitive to changes in the model or small changes of the judgements.

The ranking may thus be judged robust from this point of view.

The experts

As has been noted elsewhere, the original idea was to repeat the ranking with the aid of a larger group of experts but this was decided to be unnecessary as the results were so clear. One objection that might be raised is that a change of experts might have changed the result.

This might be phrased in other words; Is the group of experts used representative of a larger population of experts?

One can look at this in two ways:

- You should see to it that the group has a suitable composition by picking people with different backgrounds so that the total base of knowledge is wide enough. This selection was done on a subjective basis. However, the authors are of the opinion that the group of experts presented in this report had a suitable composition.
- The other way to look at it is to check if the experts are independent (in the statistical sense). If not, one might end up with a result which, though it comes from a group, just represents one opinion. Such dependence might occur if the experts have common training etc.

Dependency between the experts who participated in the ranking was evaluated with a method proposed by Baecher /9-2/.

For each expert and each ranking the deviation and the group mean was computed and expressed in standard deviation. Then the correlation matrix for the experts was calculated for all rankings at level 2. This was not done for the level 1 rankings as these are to few (4) to give a significant result. The correlation matrices are shown in Tables 9-2 a-b.

Table 9-2 a Correlation matrix. All rankings x_1---x_6

	I	II	III	IV	V	VI
I	1					
II	-.11	1				
III	-.23	-.2	1			
IV	-.33	-.1	-.31	1		
V	-.12	-.2	-.23	-.18	1	
VI	-.21	.11	-.18	-.1	-.4	1

Table 9-2 b Corrrelation matrix. Level 2 ranking x_1--x_6

	I	II	III	IV	V	VI
I	1					
II	-.21	1				
III	-.02	-.46	1			
IV	-.53	.14	-.56	1		
V	.14	.07	-.25	-.24	1	
VI	-.21	.32	-.29	.19	-.58	1

The table shows that there is not a large correlation in the matrix for all judgements (Table 9.2.a). This is natural as there are so many different judgements and it is unlikely that all answers would correlate even if the experts were dependent. In Table 9.2.b there are no large positive correlations either, the largest being 0.32. It therefore seems probable that the experts are indeed independent.

Another and important question is that of the risk of misunderstanding of the model and thus of the criteria for judgements. This might be a problem when the ranking is done by mail compared to that of a group session. As the experts took part in the design of the hierarchic structure the authors feel that most of this type of risk was eliminated. It was, however, noticed as a result of the meeting with the expert group that some such misunderstandings did exist. They were discussed at the meeting and some changes were made in the judgements. At this meeting the experts were expressly asked if they could think of any factors that might change the ranking order of the repository concepts, but the answer was negative.

It is therefore the opinion of the authors of this report that the result of the ranking is robust and that further ranking with a large group of experts would not provide sufficient new information. The ranking result with respect to KBS-3 as preferred concept should remain the same.

10 DISCUSSION

This chapter constitutes a discussion and explanation to the result of the ranking. Presented viewpoints and technical judgements based on the authors' opinion about the concepts and points of view put forward by the expert group.

Based on gained experience from the performed ranking, the common opinion among the experts in the group is that the Analytic Hierarchy Process (AHP) was a suitable method for the technical comparison of repository concepts in PASS and a good tool in order to get the necessary general view of the comparison.

The common opinion among the experts was that the possibility that another concept than the KBS-3 would be the preferred concept even with vast R&D efforts is very unlikely. A ranking that would place KBS-3 second would demand a new repository concept or some new demands or prerequisites, today unknown.

The significance of the relative difference between the concepts is hard to evaluate but important for the final ranking is that the KBS-3 concept is the preferred concept by all experts and in every respect has a higher ranking than the others.

Based on an analysis of the ranking result and discussions with the expert group Technical Feasibility is judged to be the most important criterion for the comparison.

Interesting to analyse is what technical factors that are important and significant for the ranking result. The discussion below deals with the main activities; Technical Feasibility, Construction, Operation and Human Intrusion.

Technical Feasibility

All three mined repository concepts are based on well proven technology or technology that has been used in adjacent fields. One fact when comparing the technical maturity is that KBS-3 has been continously scrutinized during a 10-year period within the frame of the annual cost studies for determining the fee on nuclear power production for the back-end cycle, while less attention has been paid to technical matters of MLH and VLH. A conclusion however, which was supported by the expert group, is that there are no major differences between the mined repository concepts according to technical maturity of suggested technologies for construction and disposal and according to potential for future developments. It is consitued to be a matter of time and resourcees to reach the same level of confidence in for instance equipment for MLH and VLH as is now the case for KBS-3.

Compared to the mined repository concepts, the VDH concept is based on a much more novel technology. Deep boreholes of the sizes discussed have not been drilled before, nor have the suggested casings been manufactured and installed. Suggested design is derived from professional judgements based on oil well drilling technique and deep boreholes in crystalline rock. In order to go forward with the development work, it is probably necessary to test and prove the technology in a full scale test. Also negative for the deep borehole concept is that all type of geological investiga tions will be more difficult and expensive to perform. The result of geological investigations for depths down to about 4 km will always be more vague compared to investigations for a more shallow located repository. The existence of a high salinity gradient that will prohibit migration of radionuclides to the biosphere might change the prerequisites for the concept.

The opinion among the experts was that the present status in technical maturity and potential for developments for all mined concepts is good enough for providing the basis for an accurate judgement on differences in technical feasibility. The VDH concept, however, is based on a more novel technology and especially the deposition procedure needs to be analysed in more detail.

Construction

The geological investigation process will be an integrated part of the construction work. Surface investigation and the final geological quality designation of the bedrock surrounding the repository will be facilitated by a fairly compact layout as for the KBS-3 and MLH concepts. In order to facilitate geological investigation during construction the layout should include a ramp down to the repository level instead of only vertical shafts. From the ramp it will be possible to drill investigation boreholes and to perform other types of geological observations. An investigation tunnel, which is included in the VLH concept, might facilitate the investigation work at the repository level and be an important source of information in the decision process for the final layout. In addition to gaining knowledge about the geology during construction, the investigation tunnel could also be used for control during any requested time frame after final sealing of the repository. If demanded, investigation tunnel(s) could also be incorporated in the KBS-3 and MLH concepts.

The requested geological investigation will be much more difficult and costly for the VDH concept due to a layout that is distributed over a fairly large area and a considerable depth down to the repository level.

No major pros or cons according to construction methods have been identified for the mined repository concepts. Some development work will of course be needed but this work will mostly be concentrated to adjustments and tests of available technique for the specific objective of construction of a nuclear repository. Comparison between construction methods for mined repositories and deep drilling and running casing in the sizes discussed shows that the latter concept is based on a more novel technology with larger demand for R&D.

A small size of the repository and thus a reduced volume of excavated rock is positive from several points of view such as cost, safety during construction and environmental issues related to construction. There are no major differences between the concepts but a reduction of excavated rock volumes for ramp, shafts and tunnels will be an important part of future design work.

One advantage with tunnels constructed by boring techniques is that the disturbed zone around the tunnel is reduced, due to a favourable geometry and no impact from blasting. If this will be an important prerequisite, the tunnels for the KBS-3 concept could also be constructed by boring technique (TBM).

Operation

Deposition of canisters is facilitated in the KBS-3 concept due to a fairly small and light canister (compared to the VLH canister) that is individually emplaced in vertical boreholes in the bottom of a disposal tunnel. Also positive is that the canister is shielded during transportation and handling with limited risk for radiation. After the canister is placed in position the rock and the bentonite permits a sufficient shield against radiation for allowing the work to continue in the tunnels. The comparatively large size of the storage tunnels will facilitate transportation of canisters and also be favourable if any work needs to be carried out during the deposition procedure such as retrieving a stuck canister.

For the KBS-3 concept final positioning of the bentonite barrier around the canister could be carried out with good quality control because the bentonite is placed in position before deposition of the canister.

For the MLH and VLH concepts the deposition procedure is influenced by the previously stored canister as the canisters are stored one after each other in a horizontal position. In order to transport and deposit the canisters in a long, circular (1.6 or 2.4 m diameter) tunnel a fairly complicated transport system will be needed. Proposals for transport systems have been made for the two concepts and both systems have been judged feasible but with a minor pro for the VLH concept. All reverse actions due to any problem during transportation or deposition will be difficult to handle due to the very limited space within the tunnels. Radiation protection will not be possible all the time for VLH due to limited space in the tunnels and large canisters.

Positioning of the surrounding bentonite blocks and quality controll have been judged to be more complicated for a canister placed in a horizontal position.

The risk and probability for sabotage directed towards the canister during handling in the service area at surface and in the sub-surface facility is very small for all three mined repository concepts.

Suggested technique for deposition of canisters for the VDH concept involves several unproven actions with risk for damage of one or several canisters. As deposition is carried out without visual control the risk for emplacing a damaged canister is larger than for the other concepts. Deposition of canisters and sealing of the repository constitutes a major technical disadvantage for the VDH concept.

Another negative factor for the VDH concept is the large areal distribution of the repository with more demand for transportation of canisters outside controlled areas compared to the other concepts. The vast number and fairly light weight of the canisters makes it more vulnerable for any outside action directed towards the canisters. The canister is also vulnerable for sabotage during lifting and tripping into the borehole. Personnel at the rigfloor could also wilfully let the drillstring fall free into the borehole with ensuring damage to one or several canisters.

Post-closure

The criterion post-closure includes only human intrusion. Other criteria dealing with the long time performance of the repository are discussed in connection with the safety analysis of the different repository concepts.

Three different types of human intrusion are foreseen:

- Sabotage or any other outside action in order to damage the repository and/or discharge of radioactive nuclides
- Actions by mistake such as drilling into a repository
- Political decision to recover the waste

For the ranking of the repository concepts and thus the weight in the ranking the importance of human intrusion is less compared to other discussed criteria. An analysis shows that there is no major difference between the concepts with respect to human intrusion. Of interest is that the advantage of a deep borehole repository is limited as it is fairly easy to retrieve canisters by drilling into the boreholes and by using overcoring technique.

LIST OF REFERENCES

Chapter 1

1-1 PLAN 92. Costs for management of the radioactive waste from nuclear power production
June 1992
SKB Technical Report TR 92-24

1-2 Juhlin C, Sandstedt H
December 1989
Storage of nuclear waste in very deep boreholes: Feasibility study and assessment of economic potential
SKB Technical Report TR 89-39

1-3 Sandstedt H, Wichmann C, Pusch R, Börgesson L, Lönnerberg B
August 1991
Storage of nuclear waste in long boreholes
SKB Technical TR 91-35

1-4 Jansson L
April 1992
PASS-Method for horizontal emplacement of KBS-3 type canister in 1.6 m diameter drifts
SKB Interim report AR 92-39

Chapter 2

2-1 Same as reference 1-1

2-2 Same as reference 1-4

2-3 Same as reference 1-3

2-4 Same as reference 1-2

Chapter 3

3-1 Saaty Th. L
1990
The Analythic Hierarchy Process (2nd. ed)
RWS Publications, Pittsburgh, USA

Chapter 4

4-1 Same as reference 3-1

4-2 Manual Expert Choice software

Chapter 7

7-1 Birgersson L, Skagius K, Wiborg M, Widén H
September 1992
Analysis of performance and long term safety of repository concepts within the PASS study
SKB Technical Report TR- 92-43

Chapter 9

9-1 Same as reference 4-2

9-2 Baecher, G. B
1979
Correlation among experts' opinions
Unpublished manuscript MIT Boston

Appendix 1

ANALYTICAL HIERARCHY PROCESS, AHP-

PAIRWISE COMPARISONS AND EVALUATION

EVALUATION OF PAIRWISE COMPARISON IN THE AHP

The following example has been included in order to facilitate the reader's understanding of the principles of the AHP. It is simplified and it should be noted that although the computation methods give fairly satisfactory results, a more rigorous method based on eigenvectors is used in the computer program used in the actual study.

Hierarchic structure

The structure which is part of the main structure used is illustrated in Figure 1.

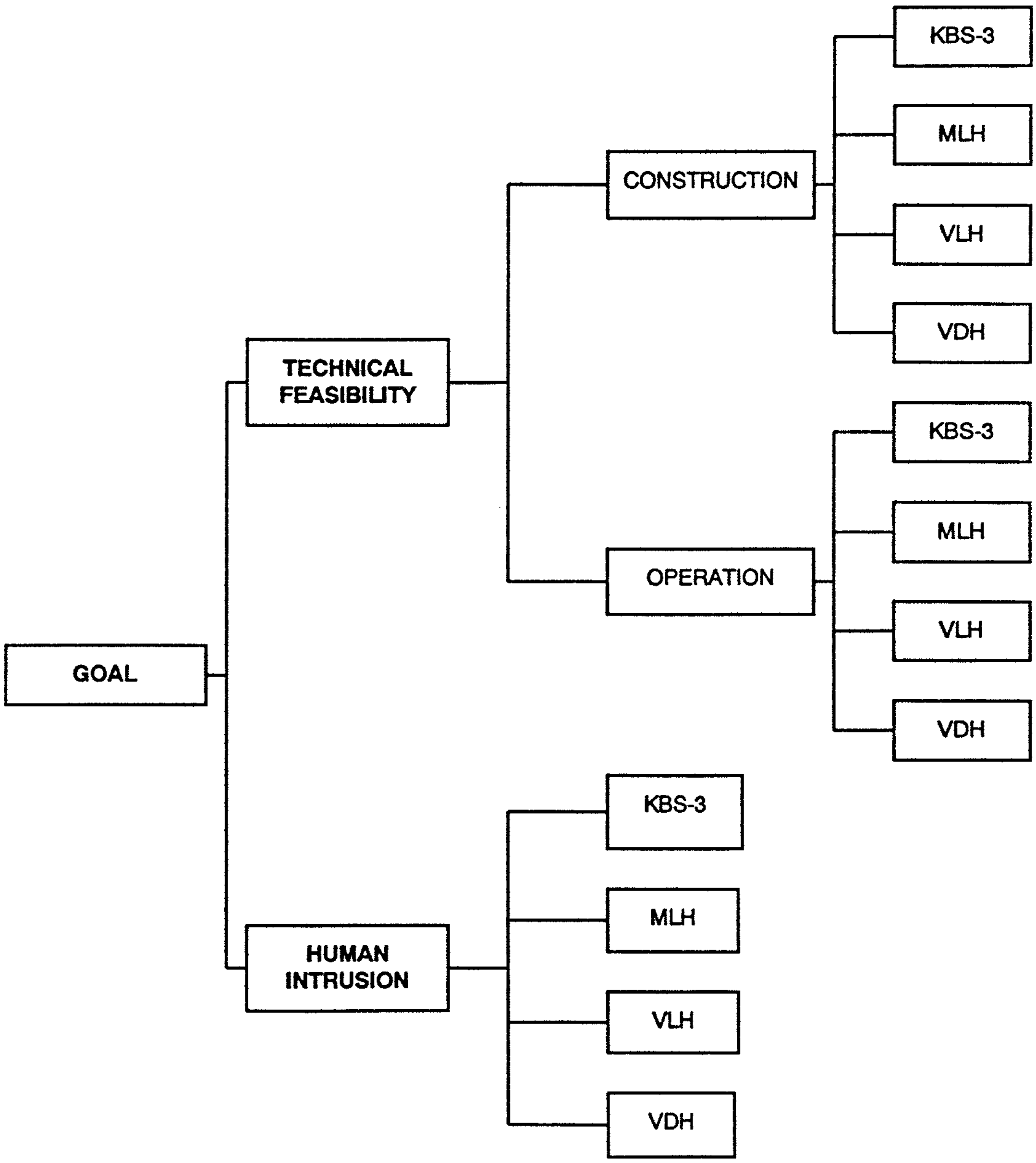


Figure 1 Hierarchic structure

Pairwise comparison

The pairwise comparison, starts from the top and all comparisons are made with regard to the next higher level.

A First TECHNICAL FEASIBILITY is compared to HUMAN INTRUSION with regard to goal. The expert considers TECHNICAL FEASIBILITY to be moderately more important for the goal than HUMAN INTRUSION or in figures: 3 times more important (the used scale is presented in chapter 4 of this report). This could be expressed in matrix form:

	TECHNICAL FEASIBILITY	HUMAN INTRUSION
TECHNICAL FEASIBILITY	1	3
HUMAN INTRUSION		1

B On the next lower level OPERATION is compared to CONSTRUCTION with regard to TECHNICAL FEASIBILITY. (N.b not to GOAL). They are considered equally important by the experts. This could be expressed in matrix form:

	CONSTRUCTION	OPERATION
CONSTRUCTION	1	1
OPERATION		1

After all the criteria have thus been compared, all the alternatives are compared with regard to the respective criterion on the next higher level. Thus there will be three such comparisons, with regard to HUMAN INTRUSION, CONSTRUCTION and OPERATION, respectively.

For CONSTRUCTION the experts gave the following judgement:

	KBS-3	MLH	VLH	VDH
KBS-3		1	1/3	3
MLH			1/3	3
VLH				5
VDH				

In the matrix the notation 1/3 means that the alternative in the column head is preferred to the alternative in the row label. Thus the expert prefers VLH to both KBS-3 and MLH. He also considers VLH to be 5 times more preferable than VDH.

Evaluation

The evaluation is normally done with the aid of a computer. The method shown below is simpler but not as accurate and is included primarily to illustrate the computation of weights at different levels in the hierarchic structure.

Evaluation is done from the top and downwards. First TECHNICAL FEASIBILITY is compared to HUMAN INTRUSION with respect to GOAL. The judgements given by the expert is entered into a (square) matrix. In order to normalise the matrix the figures in each column are added, see Table 1.

Table 1

	TECHNICAL FEASIBILITY	HUMAN INTRUSION
TECHNICAL FEASIBILITY	1	3
HUMAN INTRUSION	1/3	1
Column sum	4/3	4

In the next step each element in the matrix is divided by its respective column sum and in the matrix thus obtained all rows are added. The relative weights (relative to GOAL) are obtained by means of the row values, i.e. the row sums are divided by the number of elements in each row, in this case two. The result is presented in Table 2.

Table 2

	TECHNICAL FEASIBILITY	HUMAN INTRUSION	Row sum	Weight
TECHNICAL FEASIBILITY	0,75	0,75	1,5	0,75
HUMAN INTRUSION	0,25	0,25	0,5	0,25

On the next lower level OPERATION is compared to CONSTRUCTION. The relative weights (n.b. relative to the next higher level i.e TECHNICAL FEASIBILITY) is obtained by means of the same procedure, see Tables 3 and 4.

Table 3

	CONSTRUCTION	OPERATION
CONSTRUCTION	1	1
OPERATION	1	1
Column sum	2	2

Table 4

	CONSTRUCTION	OPERATION	Row sum	Weight
CONSTRUCTION	0,5	0,5	1	0,5
OPERATION	0,5	0,5	1	0,5

Finally, at the lowest level the alternatives are compared to one another relative to CONSTRUCTION, see tables Table 5 and 6

Table 5

	KBS-3	MLH	VLH	VDH
KBS-3	1	1	1/3	3
MLH	1	1	1/3	3
VLH	3	3	1	5
VDH	1/3	1/3	1/5	1
Column sum	5 1/3	5 1/3	1 13/15	12

Table 6

	KBS-3	MLH	VLH	VDH	Row sum	Weight
KBS-3	0,188	0,188	0,179	0,25	0,804	0,201
MLH	0,188	0,188	0,179	0,25	0,804	0,201
VLH	0,563	0,563	0,536	0,417	2,077	0,519
VDH	0,062	0,062	0,107	0,083	0,315	0,079

To get the global weights, that is the weights relative to GOAL, for the different alternatives for this branch of the hierarchic structure, the weights for the different levels are multiplied; (Weight of TECHNICAL FEASIBILITY relative to GOAL) x (Weight of CONSTRUCTION relative to TECHNICAL FEASIBILITY) x (Weight of alternative relative to CONSTRUCTION):

KBS-3	0,75 x 0,5 x 0,201 = 0,075
MLH	0,75 x 0,5 x 0,201 = 0,07
VLH	0,75 x 0,5 x 0,519 = 0,194
VDH	0,75 x 0,5 x 0,079 = 0,030

As the final step to get the overall weights for alternatives, their global weights for each branch in the hierarchic structure are added. For instance, the following global weights were found for the different branches of the structure shown above as Figure 1 for the alternative KBS-3.

BRANCH	Global weight for branch
CONSTRUCTION—TECHNICAL FEASIBILITY—GOAL	0.750
OPERATION—TECHNICAL FEASIBILITY—GOAL	0.193
HUMAN INTRUSION—GOAL	0.063
WEIGHT OF ALTERNATIVE	0.331

Appendix 2

BASIS FOR THE TECHNICAL COMPARISON OF THE KBS-3, MLH, VLH AND VDH CONCEPTS IN PASS

TABLE OF CONTENT

1 GENERAL

This appendix constitutes a guideline and a basis for the performed ranking operation. The criterias for comparison are based on propoals put forward by H Sandstedt during phase 1, interviews with the expert group and discussions with personnel from SKB.

The hierarchic structure for comparison has been divided into technical feasibility (design), construction, operation and post-closure. Post-closure includes only the criterion human intrusion. Factors related to the long term safety function of the repository are analysed in the safety analysis of the four repository concepts and presented in a separate report.

2 TECHNICAL FEASIBILITY

All proposed repository concepts have been considered feasible concerning construction and operation. There is, however, fairly large differences in proposed techniques for the different concepts. Some of the involved techniques must be judged as "proven technology", others have been used in adjacent fields and others are mostly based on design work in the office. One problem when comparing the technical level is that some of the concepts are fairly new (MLH and VLH) and others like the KBS-3 have been studied for about 10 years.

The purpose with the comparison of technical feasibility is to get an overall judgement about the concepts which also include factors like technical maturity, the possibility to succeed with construction works, deposition of canisters etc.

3 CONSTRUCTION

Construction includes the following Essential Characteristics:

- Geological investigations
- Construction techniques
- Safety
- Environment

3.1 Geological investigations

A comparison of the different concepts should include an analysis of the adjustability of the repository layout to the established conceptual geological model. Also important for comparison are the prerequisities for geological site characterization before and during the construction period and the possibility to establish an accurate geological model of the rock volume surrounding the repository.

Based on the result from the geological investigations, it might be necessary to exclude some areas from disposal of canisters with waste. Information about unsuitable areas should if possible be gained early during construction in order to change the layout or to construct the needed additional deposition boreholes or tunnels.

The quality verification of a repository site requires a detailed information of the local geological characteristics of the bedrock. The rock quality designation process starts with the surface investigations and proceeds continuously during the construction period. The data needed for licensing will be similar for the KBS-3, MLH and VLH concepts. The licensing for the VDH concept must, due to the great depth of the repository, be based on a more simplified geological model.

A concept that permits an early characterization of the bedrock is desirable, due to the possibility to adapt the layout to the prevailing geology.

Since the surface investigation techniques will be limited in acquiring detailed data it will probably be necessary to conduct some of the geological investigations from underground. The final location within a chosen site and layout of the repository will be adjusted according to obtained information during the construction period. Another reason is to minimize the number of boreholes in a potential repository area. Investigation drilling from underground requires shorter boreholes which makes it easier to hit the requested target. Shorter boreholes will also be of advantage from an economic point of view.

When discussing the site characterization process with regard to different repository concepts it is important to determine the needed accuracy of the quality verification for different phases of the project.

The analysis of the adjustability and the prerequisities for the geological investigations of the different concepts is based on a generalized model of a typical Swedish bedrock compiled by Kaj Ahlbom, Conterra. The generic model is based on the geological investigations that have been carried out by SKB since 1977. Because of the generic nature of the model it will not be directely applicable for the final site in all details. The final layout of the repository with attached structures such as ramp and shafts must be based on local conditions at the selected site.

Geological model

The repository should be located in a block of rock surrounded by regional fracture zones. The bedrock within the block should be favourable for construction of the repository and act as a barrier for radionuclide migration to the biosphere. Of major importance for the localisation of the repository is the distribution of fracture zones and the hydraulic properties of the rock. The comparison of different repository concepts will be based on the fracture distribution presented in table 3-1. This model is probably applicable for depths down to about 1000 m.

Table 3-1 Fracture distribution for a typical Swedish bedrock

(Generic model compiled by K Ahlbom, SKB Working Report AR 91-15)

Fracture	Spacing	Hydraulic conducitivity
Regional fracture zones 1st order	7 km x 3 km	$k = 10^{-7}$ m/s
Fracture zones 2nd order	800 m x 400 m	$k = 10^{-8}$ m/s
Fracture zones 3de order	100 m x 100 m	$k = 10^{-9}$ m/s
Bedrock (Rock mass including fractures of 4th order	0.8 m x 0.8 m	$k = 10^{-11}$ m/s
Major sub-horizontal fracture zones, one zone every 700 m	700 m	$k = 10^{-7}$ m/s

It will be more difficult to establish a geological model for a deep located repository such as the VDH concept. Fairly little information exists about the geology of Swedish bedrock at depth, and it will be more difficult to investigate the bedrock to the same accuracy as for a shallower location. However, some general geological conditions need to be considered for a deep seated repository:

- The number of fracture zones will decrease with depth (based on measurement in the Gravberg-1 borehole)
- The possible existence of several sub-horizontal fracture zones above the repository that might prohibit transports of radionuclides to ground surface
- The existence of an increasing salt gradient at a depth that might prohibit transports of radionuclides to surface

KBS-3 and MLH concepts

Adjustability of the layout

The area needed for the repository is about 1x1 km. The respect distance to regional fracture zones should be more than 100 m. In order to reduce the needed area a multi-level storage facility is also possible. The type of access to the repository level is not yet fully decided on and both shafts or ramp, within or outside the repository rock block are possible. For the technical comparison of concepts it should be anticipated that the main access to the repository should consist of a ramp within the repository rock block.

With the fairly small areal extension of the repository compared to the rock block and the flexible layout there should be no problem to find suitable geological conditions within a selected rock block.

Geological investigations

The geological surface investigations will be performed according to the procedures for site investigations developed by SKB.

The investigation process for rock quality designation will be integrated with the construction phases that will be divided into four main stages:

- Excavation of access ramp and vertical shafts
- Excavation of access and main tunnel
- Excavation of deposition tunnels (For MLH, drilling of deposition tunnels)
- Drilling of deposition holes

The layout of the ramp will among other factors be based on the prevailing geological conditions and requested geological information. The direction of the main tunnel will be based on surface investigations and investigation boreholes from the access tunnel. If less favourable rock is encountered during construction the main tunnel will, with this approach, act as an investigation tunnel.

The flexibility of the layout is significant at two main occasions during the repository construction. The first occasion is before construction of the main tunnel and secondly when siting the individual deposition boreholes or deposition tunnels.

Final characterization of the bedrock surrounding the repository

A detailed verification of the geological characteristics of the site will be obtained after the deposition tunnels are excavated. The work with the final predictive geological model will be facilitated by the compact layout of the KBS-3 repository.

VLH concept

Adjustability of the layout

The area needed for the repository is about 4.5 x 0.3 km. The respect distance to regional fracture zones should be more than 100 m. The design of the concept presumes that the deposition tunnels cross one regional fracture zone. Depending on the characteristics of the fracture zone any required part of the tunnel around the zone will be sealed off and not be used for storage of radioactive waste. The access to the repository is suggested to consist of a ramp down to the repository level. The ramp could be constructed within or outside the repository rock block.

According to the model for typical Swedish bedrock it should be possible to locate the repository to one single rock block. It is also possible to construct the repository with several shorter, parallel tunnels or in a multi-level mode in order to reduce the length of the repository.

Geological investigations will be facilitated with an investigation tunnel below the repository and it should be possible to accommodate the final layout to the prevailing geology.

.Geological investigations

The geological characterization program needed for the localization of a repository consisting of long tunnels will not differ in principle from what has been suggested for the KBS-3 and MLH concepts. However, in order to obtain the same information the program will be more extensive and costly due to the length of the repository. The approach suggested is therefore to conduct most of the investigations from underground during construction and to implement an investigation tunnel in the repository layout. The rock quality designation process will be integrated with the construction phases that will be divided into three main stages:

- Excavation of access ramp and shafts
- Excavation of investigation tunnel
- Excavation of deposition tunnels

The ramp down to the repository will only cover a part of the repository due to the long extension of the deposition tunnels. The obtained information will, however, be valuable for the preliminary layout of the repository and the direction of the investigation tunnel.

The flexibility of the layout is significant at two main occasions during the repository construction. The first occasion is before construction of the investigation tunnel and secondly when siting the deposition tunnels. During construction it will be possible to extend the deposition tunnels into a more suitable geology.

The direction of the deposition tunnels will basically be based on the result from the investigation tunnel and boreholes drilled from the tunnel. The design with an investigation tunnel makes it possible to evaluate the characteristics of the bedrock at an early stage and to locate the deposition tunnels to a suitable rock mass.

Final characterization of the bedrock surrounding the repository

The final verification of the geological characteristics will be more difficult compared to the KBS-3 concept due to the length of the repository and thus a larger surrounding rock volume.

VDH concept

Adjustability of the layout

The area needed for the repository is about 10 km^2. The final size of the area will, beside geological characteristics of the site, also be dependent on the final distance between the boreholes.

This distance will depend on the following factors:

- Obtained deviation of each single borehole during drilling
- Suitable locations for drilling sites (needed area is about 100 x 100 m) within the rock block.
- Dip of regional fracture zones

The deposition boreholes should not be allowed to penetrate any major fracture zones. Due to the inclination of the fracture zones and the difficulty to evaluate the inclination the boreholes need to be drilled with a fairly long respect distance to major fracture zones. The problem with dip of major fracture zones and the siting of boreholes is illustrated by Figure 3-1 which is based on a fracture dip of 70 degrees to the horizontal. Major fracture zones should also be avoided from a drilling point of view.

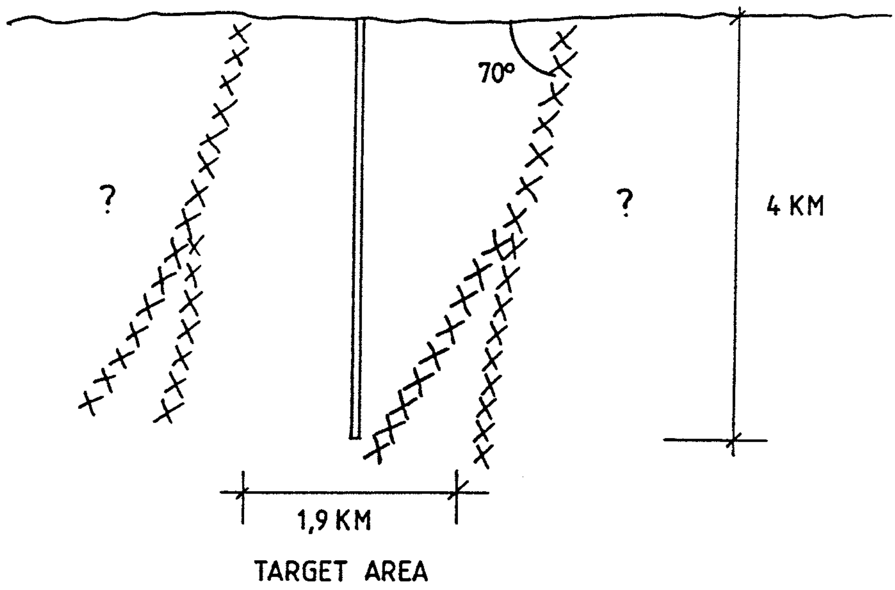


Figure 3-1 Respect distance to regional fracture zones for the VDH concept

Geological investigations

The necessary geological surface investigations for the localization of a deep borehole repository will in principle not differ from what has been suggested for the mined repositories KBS-3 and VLH. However, due to the great depth and the large areal extension of the repository the investigations will be based more on geophysical surface investigation techniques, mainly seismic soundings than on investigation boreholes.

The rock quality designation process will be integrated with the drilling of the deposition boreholes. Cross borehole investigation techniques will be possible, but dependent on final distance between the boreholes. With seismic techniques (VSP) it will be possible to locate large fractures in the bedrock. With available logging techniques a detailed knowledge about the bedrock is only obtained for the rock close to the boreholes (a couple of metres).

Final characterization of the bedrock surrounding the repository

The final verification of the geological characteristics will be less detailed compared to the characterization of the rock mass surrounding a mined repository.

Criteria for comparison

- Prerequisities for surface investigations
- Adjustability to the prevailing geology
- Final characterization of the bedrock surrounding the repository

3.2 Construction techniques

A comparison of the activity construction is difficult due to the great difference in technology between the three mined repository concepts and the deep borehole (VDH). For the final comparison of concepts it is also important to recognize that the deep borehole concept is based on a more novel technology compared to the mined concepts.

One of the largest differences between the mined repository concepts is that for the VLH concept almost all excavated tunnels are used for storage of canisters. This is the main reason for the differences in excavated rock volumes and also in cost for construction. A reduced size of the repository is also positive for several other reasons such as the need for rock dumps, safety, the need for supply systems etc. Another important difference is that tunnels for the KBS-3 concept are constructed by drilling and blasting and for the VLH concept by tunnel boring technique, TBM. The MLH concept is suggested to be constructed by drill and blast and horizontal raiseboring.

Both the KBS-3, MLH and VLH concepts are designed with a ramp as the main access down to the repository level. Whether the ramp should be excavated by drill and blast or modern fullface boring techniques is not yet fully decided.

The layout of the three different repository concepts is summarized below:

KBS-3

- Repository level approx. 500 m
- 1 ramp and 2 vertical shafts down to the repository level
- Total volume of excavated rock will be approx. 720.000 m^3
- About 3800 disposal holes will be drilled in the bottom of the storage tunnels

MLH

- Repository level approx. 500 m
- 1 ramp ond 2 vertical shafts down to the repository level
- Total volume of excavated rock will be approx. 530.000 m^3
- Approx. 22.000 m horizontal disposal tunnels will be drilled at the repository level
- Deposition tunnels are constructed by horizontal raise boring. Remaining tunnels at the repository level are constructed by drilling and blasting

VLH

- Repository level approx. 500 m
- 1 ramp and 2 vertical shafts don to the repository level
- Total volume of excavated rock will be approx. 330.000 m^3
- Tunnels are mainly constructed by TBM boring

VDH

- Repository level approx. 2000-4000 m
- The repository consists of 38 boreholes with a total excavated rock volume of approx. 160.000 m^3
- The boreholes are constructed by rotary drilling

Techniques for rock excavation (at the repository level)

Access, main and deposition tunnels for the KBS-3 concept are assumed to be constructed by drill and blast technique. The deposition boreholes in the bottom of the deposition tunnels will probably be drilled with blind boring technique and an equipment similar to raiseboring machines. However, a final choice of method and technology should be based on fullscale tests. For the MLH concept access and main tunnels are assumed to be constructed by drill and blast. The horizontal deposition tunnels with a diameter of 1.6 m are suggested to be constructed by horizontal raiseboring. The pilot hole included in the raiseboring procedure could be used for both geological investigations and for pre-grouting.

All tunnels for the VLH concept are assumed to be constructed by TBM technology. TBM boring in hard rock is a well proven technology. An analysis of the three excavation techniques discussed shows that all alternatives must be considered similar with regard to technical feasibility.

A negative factor that should not be neglected with the small circular tunnels for the MLH and VLH concept is the limited space available for construction works such as installation of reinforcement. In order to obtain a circular tunnel within allowed tolerances it might be necessary to precede the deposition of canisters with an enlargement of the tunnels in some sections.

Below is a summary of proposed excavation techniques at the repository level for the three mined repository concepts:

- KBS-3 Tunnels will be constructed by drill and blast. Vertical, 1.6 m diameter deposition boreholes will be drilled with blind boring technique by equipment similar to that used for raiseboring
- MLH Tunnels will be constructed by drill and blast. Horizontal, deposition tunnels, will be constructed by raiseboring
- VLH Deposition tunnels, 2.4 m diameter, will be constructed by TBM boring

Influence of the near field rock from a hydraulic point of view, due to used construction technique, is included in the safety analysis of the different repository concepts.

Rockstability /Rock support

Also important when comparing different excavation methods is to analyse the resulting quality of the tunnel. Several advantages will probably be achieved with circular tunnels due to the long time safety function of the repository:

- More stable tunnels, normally with little need for reinforcements
- Probably less influx of water due to a better stress distribution around a circular tunnel

- Less disturbance of the near field rock due to no influence from blasting and a better stress distribution around a circular tunnel

- Easier to describe the rock in the tunnel walls

From a construction operational viewpoint the rock support work will differ between the concepts. Rock support work will be more difficult in a circular tunnel with a diameter of 1.6 m compared to more normal sizes. For the comparison, factors like the need for rock support and the possibility to install required support systems should be considered.

Prerequisities for grouting

Due to a very high demand for small influx of water, grouting of the rock surrounding tunnels and other rock openings will be very important for several reasons. Besides influence from the geology, the prerequisities for grouting will differ between the concepts due to layout and construction techniques. Below is a short summary of a possible grouting strategy for the different concepts.

KBS-3

The grouting works could be carried out based on two different strategies:

A Pre-grouting of the complete tunnel section down to a depth of about 10 m below tunnel floor. This system will demand in many and long drillholes for grouting with a slow advance per round.

B Grouting around the deposition boreholes after siting of the individual boreholes. With this system the tunnel construction will proceed faster. Negative is that grouting around the deposition boreholes must probably be carried out with a fairly low pressure due to the risk of fracturing in the tunnel floor. A more stable tunnel section will be received if the storage tunnels are constructed by TBM technology.

MLH

The pilot borehole included in the raiseboring operation could be used for grouting. By using packers the grouting could be carried out in sections with grouting material suitable for each section. Due to the fairly small size of the tunnel and the grouting prerequisities the probability to achieve a tight tunnel must be judged to be fairly high.

VLH

The limited space around the TBM machine will make it difficult to direct the drillholes and to carry out the grouting operation.

From a grouting point of view it will be more difficult to achieve a tight tunnel for a 2.4 m TBM tunnel compared to a 1.6 m tunnel constructed by raiseboring.

Sensitivity of the construction techniques to sever geological condition

Severe geological conditions for tunnel construction are basically related to rock movements and influx of water. The risk for such events will, besides geological conditions, be dependent on construction methods, excavated rock volumes and length of tunnels. Experience shows that major rock movements are normally related to blasting operations. The size and shape of the excavated rock caverns will also influence the stability. A small, circular tunnel is normally more stable compared to a traditional tunnel excavated by drill and blast.

The possibility to cross difficult zones will probably differ between the concepts due to different construction techniques. The comparison of sensitivity of the construction technique to sever geological conditions for the three concepts should be concentrated to the following situations:

- KBS-3. Crossing of a severe zone with a horseshoe tunnel by drill and blast
- MLH. Crossing of a severe zone with a circular tunnel constructed by horizontal rais eboring
- VLH. Crossing of a severe zone with a circular tunnel constructed by TBM boring

Technical maturity

A comparison of technical maturity shows that both the KBS-3, MLH and the VLH concepts are based on a relatively well proven technology. Developments concerning careful blasting will be positive for reducing the disturbed zone around the tunnels. Any major cost and time reductions are not foreseen. With existing drilling techniques specially designed for drilling blind boreholes there should be no problem to drill the deposition holes in the bottom of the storage tunnels. Potential for future development.

Potential for future development

A comparison between the two mined repository concepts and the VDH concepts shows that the latter is based on a more novel technology. In order to prove the feasibility the total system must be tested including drilling, running heavy casing and liner and the deposition procedure.

An increased use of TBM technology in hard rock projects worldwide, now and inear future, will result in better machinery and construction methods. Compared to drilling and blasting the potential for cost and time reduction is larger for long tunnels constructed by different boring techniques. The penetration rates will increase due to stronger machines. A major development for the KBS-3 concept should be to use TBM technology for construction when possible.

The development of other techniques for boring of long horizontal holes (200-500 m) such as horizontal raise boring will be of interest for the MLH repository and for a compact VLH repository.

Very little demand for drilling deep, large diameter boreholes (approx. 0.5-1.5 m) is foreseen on the market in the near future. The sizes discussed are larger than any boreholes drilled by the oil and gas industry but smaller than vertical shafts used in the mining industry. Probably some deep boreholes will still be drilled for atomic bomb experiments but also this demand seems to be decreasing. However, the potential for cost reductions is larger for the VDH concept compared to the KBS-3 and VLH concepts. If the boreholes could be drilled to 4500 m and waste stored up to a depth of 1500 m then the needed number of boreholes would be reduced with 50%.

Criterias for comparison:

- Techniques for rock excavation
- Rock stability/Rock support
- Prerequisities for grouting
- Sensibility of the construction techniques to severe geological conditions
- Technical maturity
- Potential for future developments

3.3 Safety during construction

Safety during construction could be divided into safety related to the bedrock or the construction works (working hazards) and operational safety such as fire safety. Important also for construction of a waste repository is that a good security system prevents any outside action towards the repository or the construction works.

Rock related unexpected events

The risk for rock related unexpected events in addition to the prevailing geological condition will be dependent on construction techniques and volumes of excavated rock. Comparison between the mined repository concepts shows that the risk for accident must be judged to be higher for theKBS-3 concepts due to larger excavated rock volumes and the use of blasting. The risk for MLH will be lower than the KBS-3 concept but higher than the VLH due to larger excavated rock volumes and some blasting.

Compared to the mined repositories, rock related unexpected events for the VDH concept will normally only be of economic nature and should not be considered in a safety analysis (some impact might occur from an accident below surface at the rig floor).

Working hazards

The risk for accidents and injuries of personnel working sub-surface depends basically on the type of activity and excavated rock volumes. The differences in risk level between the mined concepts will be similar for working hazards as for rock related unexpected events.

A comparison between the mined repositories and the VDH concept is difficult due to a very different construction approach. Deep drilling with heavy drilling rigs involves many dangerous operations such as tripping in and out of the boreholes, work with heavy casings and high pressure fluids. A definitive safety comparison must be based on statistics but the risk level will probably be similar for the VDH concept compared to the other three concepts. The handling of quartz sand that will be used for sealing of tunnels and shafts for all mined concepts must be carried out with great care in order not to jeopardize the health of personnel.

Security

A good security system is needed in order to prevent any outside action towards the repository or the construction works. The design and operation of the security system will be similar for the three mined repository concepts. Due to the fairly small area that needs to be controlled no major difficulties are foreseen for the mined repositories (similar to a nuclear power plant).

The security control system for the VDH concept will be similar both concerning technical systems and operation. Due to several drillsites in operation at the same time, the needed security system will be larger for the VDH concept in order to achieve the same security level. One negative factor for the VDH concept that could not be neglected is the higher risk for sabotage. Sabotage could fairly easily, be directed towards drilling rigs or towards transports to and between drillsites.

Operational safety

Operational safety refers to factors such as fire safety, possibilities for emergency escape etc. From this respect the VLH concept involves some obvious disadvantages due to long tunnels that end blind.

Criteria for comparison

- Rock related unexpected events
- Operational safety
- Working hazards
- Security

3.4 Environmental impact related to construction

Several environmental issues besides discharge of radioactive nuclides will be considered in the licencing process for the localization of a repository. The construction permits are normally dependent on certain conditions in order to minimize the environmental impact during the construction period. Important issues for large underground construction works are the area affected by construction, handling of excavated rock at the ground surface, emission of noise, dust and exhaust gases. Besides emission, heavy traffic might also create discomforts such as road accidents, vibrations, psychological reminders about the disposal project etc. A minimum of transport work is desirable.

Many of the factors related to environment will depend on the volumes of excavated rock (size of the repository) such as the size of rock dumps, emission of exhaust gases and transport work. The backfilling of the repository is planned to be carried out with a mixture of quartz sand and bentonite. It is therefore anticipated that all excavated rock will be stored in one or several rock dumps at the ground surface. Due to a probable remote location re-use of excavated rock is unlikely. All drainage water must be treated (cleaned) before it can be discharged to a recepient. Most underground work will probably be carried out with the aid of electric equipment. Emission of noise, dust and exhaust gases will basically be caused by transports at the ground.

Prerequisities for KBS-3

- One working area outside the central area
- Temporary roads:
  - One road to the working area outside the central area approx. 1 km long
  - One road for excavated rock to a rock dump approx. 1 km long
- Total amount of excavated rock will be about 720.000 m^3. The volume will be about 1.100.000 m^3 after swelling
- Emission of noise, dust and exhaust gases during transportation will approx. be proportional to excavated rock volumes
- Total area required for construction:

Working area	0.01 km^2
Roads and power supply	0.02 km^2
Rock dump (height approx. 9 m)	0.12 km^2
T otal	0.15 km^2

Prerequisities for MLH

The prerequisities for MLH, will be the same as for KBS-3 besides:

- The total amount of excavated rock will be about 530.000 m^3. The volume will after swelling be about 850.000 m^3
- Total area required for construction:

Working area	0.01 km^2
Roads and power supply	0.02 km^2
Rock dump (hight approx. 9 m)	0.09 km^2
Total	0.12 km^2

Prerequisities for VLH

- No working areas will be needed outside the central area
- Temporary roads:
  - One road for excavated rock to a rock dump approx. 1 km long
  - Total amount of excavated rock will be about 330.000 m^3. After swelling the volume will be about 530.000 m^3
  - Emission of noise, dust and exhaust gases will approx. be proportional to excavated rock volumes and time for construction
  - No extra supply for items such as fresh water and electric power wille needed outside the central area

- Total area required for construction:

Working area	0.01 km²
Roads and power supply	0.02 km²
Rock dump (height approx. 9 m)	0.06 km²
Total	0.09 km²

Prerequisities for VDH

- 38 working areas, drilling sites, will be needed for the drilling and deposition of canisters. Each site will be approx. 100 x 100 m
- A system of transport roads will be needed in order to connect the drilling sites with the central area. The length of the roads will be approx. 26 km for a distance of 500 m between the boreholes
- The total amount of excavated rock will be about 160.000 m³. The volume will be about 250.000 m³ after swelling. All rock cuttings will be stored at the respective drillsite
- Each site must be connected with an electric powerline (10.000 V) during drilling and deposition of canisters
- Fresh water will be supplied from drilled boreholes close to the drillsite
- Emission of exhaust gases will be created by transportation of equipment to the drill sites and internal transportation at the site
- Each drillsite will create emission of noise during drilling and deposition. The noise levels are similar to those at normal construction sites
- The drilling of the holes and the deposition of canisters is carried out in one operation.
- Total area outside the encapsulation station affected by the construction:

Working area	0.38 km²
Roads and power supply	0.53 km²
Rock dump	———
Total	0.81 km²

Criteria for comparison:

- Area affected by the construction
- Rock dump
- Emissions (noise, dust and exhaust gases)
- Transport works
- No drainage water will be pumped out from the rock

4 OPERATION

Operation includes the following Essential Characteristics:

- Transportation
- Deposition
- Backfilling
- Sealing
- Reversability
- Safety
- Environment
- Management of the repository

4.1 Transportation of canisters

The technical comparison of transport system for canisters will mainly be based on a safety analysis for the three different repository concepts. Important criteria are that a damaged canister should not be deposited and that canisters should not be damaged after deposition. It is also important to analyse the risk for discharge of radionuclides during transportation and deposition. This study will not include any estimates of total probabilities, nor any detailed studies of probabilities for different events as the objective of this study is to make a qualitative comparison of the different concepts.

The risk for damage will depend on the type of transportation system, number of canisters, size and weight of canisters, number of hoisting activities etc. It is also important to consider the technique and the possibilities to abandon the deposition procedure and the transport of canisters back to the encapsulation station. When discussing damages of canisters caused by various accidents it is important to consider the probability for the following type of events:

- Large damage that might contaminate large areas with radionuclides (The risk for such an event should be eliminated by technical measures)
- Damages that will be detected and where the canister can be transported back to the encapsulation station
- Damages that are not detected and could cause leakage of radionuclides in a long time perspective

The probabilities for damage of canisters during transportation have been evaluated with the aid of a simplified fault-tree approach considering only main events. For this reason the transport operation has been aggregated into events such as handling, transports etc. With this approach the probability of failure can be expressed as the sum of probabilities of occurences of these events. As many of these probabilities are common or are of a comparable type for all concepts they can be deleted in the comparison.

One problem with this brief analysis is the influence of the number of canisters on the probability of an undesirable event. In the comparison the total number of for example lifting operations at one place is treated as one event. In order to compare KBS-3 and MLH (3800 canisters), VLH (1900 canisters) and VDH (11000 canisters) the influence of the number of canisters and the number of times the operation is repeated needs to be considered. As the repeated action can be looked upon as a serial system, with each repetition as a "link in the chain", bounds for the system probabilities can be calculated.

Probabilities for system failure as a function of probability of damage at a single operation is presented in figure 4-1 for the different concepts. The system failure is calculated for the two cases of no correlation and full correlation between the elements. The question of correlation is of a fairly great importance. Narrower bounds can be calculated when the correlation is known (or can be estimated) but the calculation effort is greater. This tentative analyse shows that the transport system, due to the large number of operations, must be designed with a very low probability of damage during a single operation and with a high correlation between the operations in order to limit the system failure probability to an acceptable level.

The simplified fault-tree analysis used in the estimates is based on the transportation procedure presented below for the different concepts.

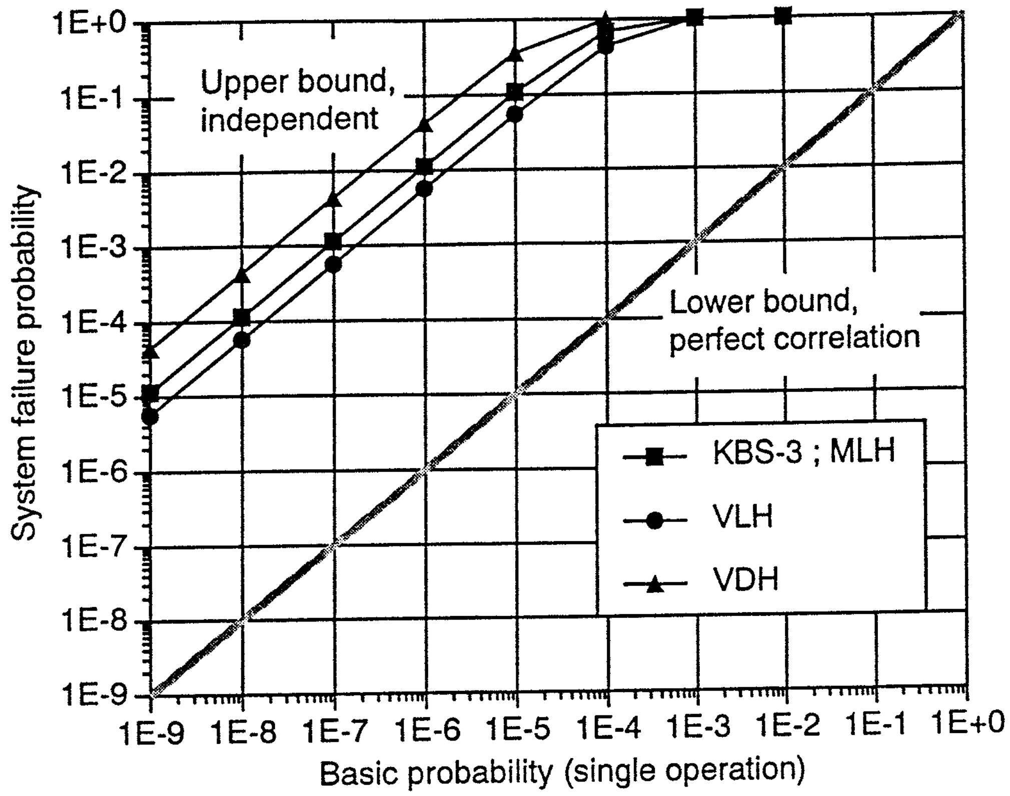


Figure 4-1 Probabilities for system failure as a function of probability of damage at a single operation for the different concepts

Summary of procedure, KBS-3 and MLH

Number of canisters	3800
Weight of canister (unshielded)	14 tons
Small height hoisting operation	3
In-plant transport	1
Sabotage while in plant	1
Transport in ramp	1
Sabotage during transport in ramp or at the repository level	1
Transport at the repository level	1
Deposition of canister	1

Summary of procedure, VLH

Number of canisters	1900
Weight of canister (unshielded)	48 tons
Small height hoisting operation	3
In-plant transport	1
Sabotage while in plant	1
Transport in ramp	1
Sabotage during transport in the ramp or at the repository level	1
Transport at the repository level	1
Jamming during transportation in the deposition tunnel	1
Deposition of canister	1

Summary of procedure, VDH

Number of canisters	11000
Weight of canisters (unshielded titanium canister)	3 tons
Small height hoisting	4
External (road) transport	1
Sabotage during road transport	1
Lowering in borehole	1
Jamming in borehole	1
Damage from a falling drillstring	1
Sabotage during deposition	1
Deposition of canister	1

Handling

"Small height hoisting" covers operations such as loading onto a truck etc. The canisters are probably designed to withstand such a fall but still there is a possibility of them being damaged and that the subsequent inspection does not detect the damage. Total number of operations for KBS-3 are 11.400, for VLH 5.700 and for VDH 44.000.

The probability of a damaged canister to be deposited in the repository will be the product of the probability of a fall and a damage to be undetected. This means that the basic probability of a canister to be damaged in this way and of the damage to go undetected is extremely small.

However, the large number of operations means that the total probability of any damage during "Small height hoisting" can be rather high, see principle figure 4-1. Based on the number of canisters the probability of an accident seems to be highest for the VDH and lowest for the VLH and with KBS-3 and MLH in between.

Transport

The risk during all transports within the encapsulation plant or in rock caverns is considered to represent the same probability, as traffic conditions can be controlled, suitable vehicles chosen etc. For transport on external roads the risk is higher, both considering probabilities of collisions etc and consequences connected with these.

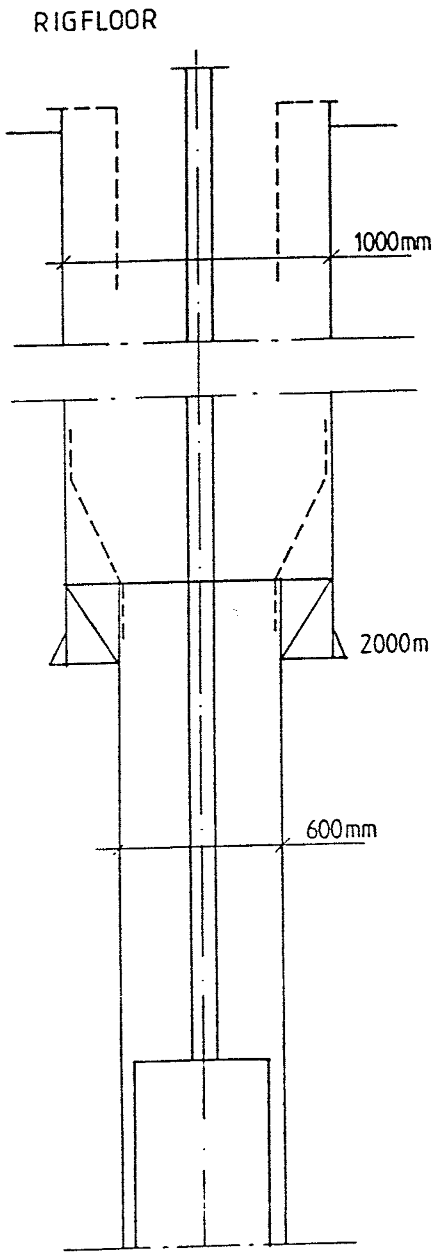
From this aspect the VDH concept has a larger probability of an accident to occur compared to the other two concepts, due to the need for transport of canisters between the encapsulation station and the drilling sites.

Transport down to the repository level

The risk for damage during transportation in the ramps will be of the same magnitude for both the KBS-3, MLH and VLH concepts. The transportation system will be designed to a very high level of safety and the procedure can be designed so as to make the degree of statistical correlation high.

In the VDH concept the canisters are lowered down to the deposition position with the aid of the drillstring. To the probability of an accident adds as a mishap with the drillstring, breaking or being dropped, which could take place both during tripping in and out of the borehole. To this is added the probability of a canister being damaged running into the deposition hole.

The above described problems and critical actions are shown in figure 4-2. As this operation is repeated many times in different locations the statistical correlation might be rather low and the system probability of damages is therefore relatively high. A falling drillstring will receive a considerable speed and is likely to damage several canisters. A probable action after such an event will be to retrieve the drillstring and seal off the borehole.



PROBLEMS/CHRITICAL ACTIONS

1. COPLING TO THE DRILLSTRING

2. TRIPPING

   - LOSS OFF DRILLSTRING

   - TWIST OFF DRILLSTRING

3. CROSS OVER BETWEEN 1000 mm CASING AND 600 mm LINER

   - DAMAGE TO THE CANISTER

   - BENDING TO THE COPLING BETWEEN THE DRILLSTRING AND CANISTER. LOSS OF CANISTER

4. DEPOSITION OF CANISTER

   - DAMAGE TO THE CANISTER DUE TO DIFFICULTIES TO MONITOR THE DEPTH AND WEIGHT ON CANISTER

   - PENETRATION OF DEPOSITION MUD BY VIBRATION

   - DIFFICULTIES TO LOOSEN THE DRILLSTRING FROM THE CANISTER

Figure 4-2 Deposition of canisters for the VDH concept

Transports at the repository level

For the KBS-3 concept all transports at the repository level are suggested to be carried out by a man operated vehicle and with a shielded canister. The transport is facilitated by fairly large tunnels with plenty of space for personnel and equipment. The risk of getting stuck during transportation is therefore relatively low.

The transportation at the repository level for the MLH concept, with deposition of canisters in 1.6 m diameter horizontal tunnels is suggested to be carried out with a railbound wagon that runs between a central area and the entrance of the deposition tunnels. This transportation system will be remotely controlled and designed with a very high degree of statistical correlation between each operation. The risk for accidents will be lower compared to systems with man operated vehicles. A similar system could also be designed for the reference concept KBS-3.

For the VLH concept all transports at the repository level are carried out in small circular tunnels with no space for shielding. The feasibility study of the concept has shown that it should be possible to design a suitable remote operating transportation system. However, with the small space between the canister and the tunnel wall the risk for getting stuck must be judged larger compared to the KBS-3 concept . Actions in order to loosen the canister will also be fairly difficult due to limited space and no protection against radiation.

For the VDH concept the "transportation at the repository level" is incorporated in the total procedure of running into the borehole and emplacement of canisters in final position.

Radiation protection

All transportation activities prior to disposal are carried out with a shielded canister for all the concepts. Due to the large size and heavy weight of the VLH canister, transportation in the 2.4 m diameter tunnels will be carried out with an unshielded canister. In order to minimize the size of the deposition tunnel for the KBS-3 concept the canister is suggested to be unshielded, but the vehicle will be equiped with a shield separating the canister from personnel during transport to the deposition hole.

Criteria for comparison:

- Handling
- Transport
- Sabotage
- Transport down <u>to</u> the repository level
- Transport <u>at</u> the repository level
- Radiation protection

4.2 Deposition of canisters

The final emplacement of the canisters are integrated with the emplacement of the surrounding bentonite barrier. The technique suggested for emplacement differs fairly much between the concepts regarding deposition technique, possibilities for quality control and protection against radiation.

Deposition technique

Deposition procedure, KBS 3

The canister will be stored individually in a vertical position in drilled boreholes in the bottom of the storage tunnels. The weight of the canister is about 14 tons with a length of 4.9 m and a diameter of 0.88 m.

The bentonite barrier will be placed in position before the canister is lifted down into the deposition hole. The integrity of the bentonite barrier is secured by a thin-walled casing pipe that is retrieved. The canister is transported inside a "box" that is tilted over the deposition hole and the canister is lowered down by a hydraulic lifting equipment. If the canister gets stuck during deposition it should be possible to retrieve the canister with the same equipment.

Radiation protection is included in the technical procedure all the time during deposition. One advantage with the KBS-3 concept is that when the canister is placed in position and covered by bentonite all works in the storage tunnels could be carried out without any consideration about radiation.

Compared to the VLH and partly the MLH concepts all works at the repository level including deposition will be facilitated by the comparatively large deposition tunnels.

Deposition procedure, MLH

The same type of canisters as for the reference concept KBS-3 will be emplaced one after each other in a horizontal position in circular drifts with a diameter of 1.6 m. Compacted bentonite will be placed between the canisters.

Transportation and deposition of the canister and the surrounding bentonite is suggested to be carried out by a "crawler" similar to a TBM body. The advantage of this transportation system is that the bentonite is placed in position in one operation. During transportation the bentonite is protected by a retrievable liner. During transportation the canister is stored inside the "crawler" which also acts as radiation protection.

The suggested transportation system will be fully remote controlled and both transportation and positioning of the bentonite and the canister will be carried out with good possibilities for quality control.

If the crawler with its enclosed canister gets stuck the retrieving operation will be fairly difficult due to the small size of the tunnel. Of advantage, however, is that personnel working in the tunnel will be fully protected against radiation by the crawler.

Deposition procedure, VLH

The canisters will be stored one after each other in horizontal position in circular deposition tunnels. The weight of the canister is about 48 tons with a length of 5.9 m (hemispherical ends) and a diameter of 1.6 m.

The positioning of the canisters is integrated with the emplacement of the bentonite barrier. Different techniques for transport and positioning of the canister in the small circular deposition tunnels have been evaluated and both railbound wagons and wagons on rubber wheels have been considered. One interesting option is to start the deposition with emplacement of a bentonite bed in the bottom of the tunnel. The next step will be to straddle the bed with a wagon and lay down the canister. The remaining bentonite blocks will be placed in position afterwards.

Quality control will be more difficult compared to the KBS-3 concept, due to the small space around the canister and no protection against radiation.

If the canister gets stuck the retrieving operation will be difficult due to an unshielded, large and heavy canister. Reloading of the canister on to the transportation wagon will also be difficult.

.Deposition procedure, VDH

The small canister with a weight of about 3 tons (depending on the type of canister) is lowered into the borehole by the drillstring. All work with the canister is directed by actions at the rig floor based on various measurements such as depth, weight of canister etc. Visual control of the deposition process is therefore not possible. The final positioning of the canister involves several difficult operations such as penetration of deposition mud and loosening the canister from the drillstring. The risk for damage of the canister during these operations must not be neglected and needs further evaluation.

Arrangements for radiation protection will be needed at the rig floor. The small size and low weight of the VDH canister will facilitate the design and installation of such equipment.

If the canister gets stuck during deposition the first option will be to abandon deposition and run out of the borehole with the canisters. If the canister is lost it will be retrieved by overcoring technique.

Technical maturity

Deposition of canisters according to the KBS-3 concept is based on a fairly simple technique and facilitated by the large space of the deposition tunnel.

Deposition of canisters for both MLH and VLH concepts is based on a design that has been judged feasible. None of the concepts has been proven and a next steep would be to make a test on a small scale. The technical procedure suggested for the VDH concept is tentative and needs further analysis.

The technical level for the deposition procedure suggested for the VDH concept will be on the same technical level as for the MLH, and VLH concepts.

Potential for future development

An evaluation of the potential for future development must be based on the planned risk analysis discussed above. For the VDH concept the proposed deposition procedure must probably be changed fairly much in order to meet requested demands for control and quality assurance.

Radiation protection

See presentation of deposition procedure.

Quality assurance

Quality assurance during deposition is related to factors such as placing the canister in the right position and detecting damages directed towards the canisters.

KBS-3

The canister is protected by a transportation cage during deposition. Good visual control is possible during the total procedure due to the large deposition tunnel.

MLH

The canister is placed into position by a specially designed machine which keeps the canister protected during the total operation. By the remote control system and TV-cameras it is considered possible to keep a good control of the deposition procedure.

VLH

Transportation and deposition will be carried out with an unshielded canister with risk for damage. With remote control and TV-cameras it is considered possible to carry out the deposition at the same level of control as for the MLH concept.

VDH

The risk for damage of the canisters is fairly high during deposition for several reasons as previously discussed. Quality control of the deposition procedure is difficult due to the fact that the canisters hang in a heavy drillstring and that all measurements are carried out at the ground surface. Visual control of the operation is not possible.

Criteria for comparison

- Deposition technique
- Technical maturity
- Potential for future developments
- Radiation protection
- Quality assurance

4.3 Emplacement of bentonite around canisters

Techniques for bentonite emplacement

Evaluation of bentonite emplacements techniques will be limited to a comparison between the three mined repository concepts. The bentonite emplacement approach for the VDH concept pays more attention to a deeper location of the repository than a low permeable bentonite buffer around the canisters.

Thebuffer around the canisters will consist of a brickwork of bentonite blocks. After water saturation and homogenization the bentonite will act as a low permeable buffer between the canister and the bedrock.

The bentonite emplacement activity is closely connected and integrated with the deposition of canisters. Below is a short review of the suggested technique for positioning of bentonite around the canisters.

Summary of emplacement procedure, KBS-3

1. Positioning of bentonite blocks in the deposition boreholes
2. Deposition of canisters
3. Positioning of bentonite blocks above the canisters
4. Assembling of steel pillars, if needed, in order to avoid vertical movements of the canister (depending on the time between deposition of canister and backfilling of the deposition tunnel)

The positioning of the bentonite blocks in the deposition boreholes will be carried out before the canister enters the deposition tunnel. This implies that the work with the bentonite blocks could be carried out with no attention to radiation and that the quality of the work could be easily inspected. Plenty of space is also available for works in the tunnel. After deposition the canister is totally embedded in bentonite and placed below in the bottom of the deposition tunnel and will not influence other activities in the tunnel.

Summary of emplacement procedure, MLH

1. Positioning of the bentonite lining (one operation) in the deposition tunnel
2. Retrieval of bentonite lining cage
3. Deposition of canister with plug of compacted bentonite

The deposition tunnels will, when they are filled with canisters, be sealed off with concrete or a temporary plug.

Summary of emplacement procedure VLH

1. Positioning of the bentonite blocks in the bottom of the deposition tunnels
2. Deposition of canisters
3. Positioning of bentonite blocks around the canister
4. Injection of bentonite slurry

The positioning of bentonite blocks will be carried out in a small diameter deposition tunnel with little space for personnel and machinery. The work is carried out close to already stored canisters with the need for radiation protection for personnel or by remote control. Of advantage for the concept is that the canisters and deposition tunnels are sealed off in the same operation.

Quality control will be more difficult compared to the KBS-3 concept but to some extent replaced by the injection of a bentonite slurry between the bentonite blocks.

During furloughs in the deposition of canisters, temporary barriers need to be constructed in connection to the canisters.

Parts of the tunnels that are not suitable for storage of canisters will also be filled with compacted bentonite blocks.

The compacted bentonite is fairly sensitive to water during positioning of the blocks and the canisters. The inflowing water must therefore be reduced to a certain level. This prerequisity puts forward a fairly high demand for grouting during the construction period.

Summary of emplacement procedure, VDH

1. Extruding deposition mud in the bottom of the borehole just above the previously emplaced canister

2. Deposition of canister together with compacted bentonite in the deposition mud

3. Sealing of the borehole at a depth of between 0 and 2 km

The bentonite buffer is suggested to be applied in two operations. A thick deposition bentonite mud will be extruded in the bottom of the borehole just above the previously stored canisters. In order to receive a sufficient seal the canister is installed together with blocks of compacted bentonite. After homogenization the bentonite constitute a low permeable seal that totally fills up the space between the canisters and borehole wall.

Technical maturity

The obtained quality of the bentonitebuffer around the canister will be vital for the repository long-term safety function. This implies that the quality and buffer effect of the barrier must meet certain requirements irrespective of repository concept. The performed studies of the different concepts have suggested emplacement techniques that have all been considered feasible from a technical viewpoint. Some further analysis will be needed in order to prove the safety and received quality for the different concepts. The latter is specially prounounced for the VDH concept. A definite choice of technique for positioning of the bentonite blocks around the canisters must be based on full scale tests.

A later analysis of the VDH concept shows that the proposed emplacement procedure including a thick deposition bentonite mud needs to be redesigned. The bearing capacity (shear strength) of the surrounding bentonite is lower than expected and a mechanical coupling between the canister and casing is probably needed.

Potential for future development

See comments below on technical maturity.

Quality assurance

The control work duringb entonite emplacement will be concentrated on ascertaining whether the requested amount of bentonite is placed around the canister and in the right position. The prerequisities for control will be influenced by the emplacement procedure and the possibility of visual control (also TV cameras etc.).

Radiation protection

Radiation protection is included in the proposed deposition and bentonite emplacement procedurefor the KBS-3, MLH and for the VDH concepts. For the VLH concept, bentonite emplacement will be carried out in two steps, before and after positioning of the canister.

The operation will be remotely controlled but it might be necessary to carry out adjustment works with personnel close to the canister.

Furloughs during emplacement of bentonite

Bentonite placed around canisters in horizontal position, as for the MLH and VLH concepts, will prevent water flow along the tunnels. During furloughs in the deposition it might be necessary to protect the bentonite at the deposition front from dripping water. The following methods have been suggested for the VLH concept and should also be valid for the MLH concept:

- Furlough 0-2 days — Plastic cover
- Furlough 2 days-1 month — Bentonite plugs coated with asphalt
- Furlough 1-12 months — Mechanical packer
- Furlough more than 12 months — Concrete plugs

No such barriers for water flow along the deposition tunnels are included in the deposition procedures for the KBS-3 concept. Water will run towards the deposition holes and depending on the amount of water and the time that the tunnels will stand open some temporary constructions will be needed in order to prevent an upward movement of the canister. A brief analysis /4-1/ indicates that a temporary construction, steel pillars, will be needed if the tunnel will stand open for more than one to two weeks.

No similar protection will be needed for the VDH concept due to the procedure with deposition in a borehole filled with a bentonite drilling fluid.

Criteria for comparison:

- Technique for bentonite emplacement
- Technical maturity
- Potential for future developments
- Quality assurance
- Radiation protection
- Furlough during bentonite emplacement

4.4 Sealing of tunnels and ramp

Tunnels and other rock openings will be sealed off by a mixture of sand (approx. 80 %) and bentonite. No detailed description is available for a proposed technical procedure. The same procedure will probably be valid for all mined repositories. However, for the completeness of the comparison, sealing of tunnels and ramp should be included in the comparison.

Criteria for comparison:

- Technique for sealing
- Technical maturity
- Potential for future development
- Quality assurance

4.5 Reversability

Reversability implies that it should be possible to retrieve canisters any time during the operation period. A need for reversability may arise during transportation, deposition or when the canisters are emplaced in final position. The reasons could be factors such as a stuck canister, a need to replace bad bentonite, a need for control of a canister at surface, political reasons etc.

KBS-3

With the canisters emplaced individually at the bottom of the deposition tunnels it will be possible to conduct transport of canisters in the tunnels without interference with other waste canisters. The canisters will probably be retrieved by overcoring technique and lifted up to the deposition tunnel for transportation to the ground surface.

MLH

A machine, similar to the deposition equipment needs to be developed. Some type of overcoring technique should be possible. Negative for the retrieving operation is that it might be necessary to retrieve several canisters before the requested canister could be reached.

VLH

Retrieving a large and heavy canister, approx. 60 tons, placed in horizontal position will be much more complicated compared to both the other concepts. A special designed equipment needs to be developed. The technique for retrieving a canister involves several steps such as liberate the canister from bentonite, load the canister to some type of wagon and transportation to ground surface. Negative is that it might be necessary to retrieve several intact canisters before the requested canister could be reached.

VDH

It will be fairly easy to retrieve the canisters by overcoring and to fish out the canisters from the borehole according to standard oilfield practice. Negative is that it might be necessary to retrieve several intact canisters before the requested canister could be reached. Due to a more fragile canister the risk for defect canisters during the retrieving operation will be greater compared to the other concepts.

Criteria for comparison:

- Reversability during transportation
- Reversability during deposition
- Reversability of canister in final position

4.6 Environmental issues related to operation

The environmental impact during operation is similar to the impact during construction. The same area will be affected besides the land used for the rock dump. This area will be restored after the construction period. Emissions and transport works will mainly be proportional to excavated rock volumes underground (see environmental issues related to construction) and the number of canisters. In this study it should be anticipated that all backfilling and sealing material will be transported to the location.

The areal distribution of the sub-surface repository presented below will influence the demand for land (The importance of this attribute will be site specific due to land owner and previous use of the land).

-	KBS-3		1 x 1 km^2
-	MLH		1 x 1 km^2
-	VLH	Approx.	0.4 x 4.5 km^2
-	VDH	Approx.	10 km^2

Also discussed lately is the possibility to locate service facilities below ground surface. For the mined repositories it will be fairly straight forward to locate needed facilities to rock caverns underground. For the VDH concept with 38 drilling sites it will be unpractical and costly to construct a sub-surface drilling site including space for a 50 m high drilling rig.

Criteria for comparison:

- Area affected during operation
- Emissions (noise, dust and exhaust gases)
- Transport works
- Areal distribution of the sub-surface reposit
- Possibility to locate facilities sub-surface

4.7 Safety

Safety refers to the risk for actions that might damage the canisters and cause migration of radioactive nuclides (dose). Besides already discussed criteria such as transportation, deposition and backfilling, the risk for sabotage should also be included in the comparison. The risk for sabotage will be fairly similar for the three mined repository concepts. Compared to the mined repositories the risk for sabotage must be judged to be higher for the VDH concept due to transports to 38 drillsites, many more and smaller canisters and the fact that the canisters are deposited with a drilling rig.

Criteria for comparison:

- Transportation
- Deposition
- Backfilling
- Sabotage

4.8 Management of the repository

No detailed studies have been performed about the management (operation) of the repository. Management of the repository in this chapter refers to all other activities during the operation period but handling of the nuclear waste. Factors that should be considered in the comparison are among others the following:

- Deposition of canisters and construction at the same time
- Need for personnel underground
- Rescue facilities
- Safety besides handling of canisters with waste:
  - Fire hazard
  - Occupational safety
- Supply systems (ventilation, water, electric power)

Comparison of management of the repository should be based on a general view of the different concepts considering the above mentioned criteria.

5 HUMAN INTRUSION

This chapter discusses human intrusion into the repository after the time when the repository is abandoned and sealed off. Three different types of human intrusion are considered:

- Sabotage or any other outside action in order to damage the repository and/or discharge of radiactive nuclides.
- Actions by mistake such as drilling into a repository.
- Political decision to recover the waste.

Sabotage

The possibility to enter the repository will depend on the amount of accesses down to the repository if such openings are still available after sealing. For a closed repository the technology and time to enter the repository is important. It will be faster and easier to enter a VDH repository with a drilling rig compared to opening up a vertical shaft or a ramp which is the case for the mined repositories. A heavy canister will be more difficult to recover than a small and light canister such as the VDH canister. However, the risk for any type of sabotage directed towards canisters stored in a closed underground repository is extremely low.

Actions by mistake

The risk for any outside action by mistake towards the repository will depend on the geographical location and geological conditions such as the existence of useful minerals (The stored waste might be considered as an ore deposit in the future) and the depth of the repository. In order to reduce the risk for outside actions (drilling) the canister horizontal surface area should be small. A deeper location as for the VDH concept is also positive from this viewpoint.

Political decision to recover the waste

None of the repository concepts has been designed in order to obstruct the possibility to recover the radioactive waste. If a political decision is taken there will be no major differences between the concepts according to the prospect to recover the canisters.

Criteria for comparison:

- Sabotage
- Actions by mistake
- Political decision to recover the canisters

REFERENCES

PLAN 92. Costs for management of the radioactive waste from nuclear power production
June 1992
SKB Technical Report TR 92-24

Jansson L
April 1992
PASS-Method for horizontal emplacement of KBS-3 type canister in 1.6 m diameter drifts
SKB Interim report AR 92-39

Sandstedt H, Wichman C, Pusch R, Börgesson L, Lönnerberg B
August 1991
Storage of nuclear waste in long boreholes
SKB Technical Report TR 91-35

Juhlin C, Sandstedt H
December 1989
Storage of nuclear waste in very deep boreholes: Feasibility study and assesment of economic potential
SKB Technical Report TR 89-35

Ahlbom K
1991
General rock characteristics
SKB Working Report AR 91-16

List of SKB reports

Annual Reports

1977-78
TR 121
KBS Technical Reports 1 – 120
Summaries
Stockholm, May 1979

1979
TR 79-28
The KBS Annual Report 1979
KBS Technical Reports 79-01 – 79-27
Summaries
Stockholm, March 1980

1980
TR 80-26
The KBS Annual Report 1980
KBS Technical Reports 80-01 – 80-25
Summaries
Stockholm, March 1981

1981
TR 81-17
The KBS Annual Report 1981
KBS Technical Reports 81-01 – 81-16
Summaries
Stockholm, April 1982

1982
TR 82-28
The KBS Annual Report 1982
KBS Technical Reports 82-01 – 82-27
Summaries
Stockholm, July 1983

1983
TR 83-77
The KBS Annual Report 1983
KBS Technical Reports 83-01 – 83-76
Summaries
Stockholm, June 1984

1984
TR 85-01
Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01 – 84-19)
Stockholm, June 1985

1985
TR 85-20
Annual Research and Development Report 1985
Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01 – 85-19)
Stockholm, May 1986

1986
TR 86-31
SKB Annual Report 1986
Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

1987
TR 87-33
SKB Annual Report 1987
Including Summaries of Technical Reports Issued during 1987
Stockholm, May 1988

1988
TR 88-32
SKB Annual Report 1988
Including Summaries of Technical Reports Issued during 1988
Stockholm, May 1989

1989
TR 89-40
SKB Annual Report 1989
Including Summaries of Technical Reports Issued during 1989
Stockholm, May 1990

1990
TR 90-46
SKB Annual Report 1990
Including Summaries of Technical Reports Issued during 1990
Stockholm, May 1991

1991
TR 91-64
SKB Annual Report 1991
Including Summaries of Technical Reports Issued during 1991
Stockholm, April 1992

Technical Reports
List of SKB Technical Reports 1992

TR 92-01
GEOTAB. Overview
Ebbe Eriksson[1], Bertil Johansson[2], Margareta Gerlach[3], Stefan Magnusson[2], Ann-Chatrin Nilsson[4], Stefan Sehlstedt[3], Tomas Stark[1]
[1]SGAB, [2]ERGODATA AB, [3]MRM Konsult AB
[4]KTH
January 1992

TR 92-02
Sternö study site. Scope of activities and main results
Kaj Ahlbom[1], Jan-Erik Andersson[2], Rune Nordqvist[2], Christer Ljunggren[3], Sven Tirén[2], Clifford Voss[4]
[1]Conterra AB, [2]Geosigma AB, [3]Renco AB,
[4]U.S. Geological Survey
January 1992

TR 92-03
Numerical groundwater flow calculations at the Finnsjön study site – extended regional area
Björn Lindbom, Anders Boghammar
Kemakta Consultants Co, Stockholm
March 1992

TR 92-04
Low temperature creep of copper intended for nuclear waste containers
P J Henderson, J-O Österberg, B Ivarsson
Swedish Institute for Metals Research, Stockholm
March 1992

TR 92-05
Boyancy flow in fractured rock with a salt gradient in the groundwater – An initital study
Johan Claesson
Department of Building Physics, Lund University, Sweden
February 1992

TR 92-06
Characterization of nearfield rock – A basis for comparison of repository concepts
Roland Pusch, Harald Hökmark
Clay Technology AB and Lund University of Technology
December 1991

TR 92-07
Discrete fracture modelling of the Finnsjön rock mass: Phase 2
J E Geier, C-L Axelsson, L Hässler, A Benabderrahmane
Golden Geosystem AB, Uppsala, Sweden
April 1992

TR 92-08
Statistical inference and comparison of stochastic models for the hydraulic conductivity at the Finnsjön site
Sven Norman
Starprog AB
April 1992

TR 92-09
Description of the transport mechanisms and pathways in the far field of a KBS-3 type repository
Mark Elert[1], Ivars Neretnieks[2], Nils Kjellbert[3], Anders Ström[3]
[1]Kemakta Konsult AB
[2]Royal Institute of Technology
[3]Swedish Nuclear Fuel and Waste Management Co
April 1992

TR 92-10
Description of groundwater chemical data in the SKB database GEOTAB prior to 1990
Sif Laurent[1], Stefan Magnusson[2], Ann-Chatrin Nilsson[3]
[1]IVL, Stockholm
[2]Ergodata AB, Göteborg
[3]Dept. of Inorg. Chemistry, KTH, Stockholm
April 1992

TR 92-11
Numerical groundwter flow calculations at the Finnsjön study site – the influence of the regional gradient
Björn Lindbom, Anders Boghammar
Kemakta Consultants Co., Stockholm, Sweden
April 1992

TR 92-12
HYDRASTAR – a code for stochastic simulation of groundwater flow
Sven Norman
Abraxas Konsult
May 1992

TR 92-13
Radionuclide solubilities to be used in SKB 91
Jordi Bruno[1], Patrik Sellin[2]
[1]MBT, Barcelona Spain
[2]SKB, Stockholm, Sweden
June 1992

TR 92-14
Numerical calculations on heterogeneity of groundwater flow
Sven Follin
Department of Land and Water Resources, Royal Institute of Technology
June 1992

TR 92-15
Kamlunge study site.
Scope of activities and main results
Kaj Ahlbom[1], Jan-Erik Andersson[2], Peter Andersson[2], Thomas Ittner[2], Christer Ljunggren[3], Sven Tirén[2]
[1]Conterra AB
[2]Geosigma AB
[3]Renco AB
May 1992

TR 92-16
Equipment for deployment of canisters with spent nuclear fuel and bentonite buffer in horisontal holes
Vesa Henttonen, Miko Suikki
JP-Engineering Oy, Raisio, Finland
June 1992

TR 92-17
The implication of fractal dimension in hydrogeology and rock mechanics
Version 1.1
W Dershowitz[1], K Redus[1], P Wallmann[1], P LaPointe[1], C-L Axelsson[2]
[1]Golder Associates Inc., Seattle, Washington, USA
[2]Golder Associates Geosystem AB, Uppsala, Sweden
February 1992

TR 92-18
Stochastic continuum simulation of mass arrival using a synthetic data set. The effect of hard and soft conditioning
Kung Chen Shan[1], Wen Xian Huan[1], Vladimir Cvetkovic[1], Anders Winberg[2]
[1] Royal Institute of Technology, Stockholm
[2] Conterra AB, Gothenburg
June 1992

TR 92-19
Partitioning and transmutation.
A review of the current state of the art
Mats Skålberg, Jan-Olov Liljenzin
Department of Nuclear Chemistry, Chalmers University of Technology
October 1992

TR 92-20
SKB 91
Final disposal of spent nuclear fuel. Importance of the bedrock for safety
SKB
May 1992

TR 92-21
The Protogine Zone.
Geology and mobility during the last 1.5 Ga
Per-Gunnar Andréasson, Agnes Rodhe
September 1992

TR 92-22
Klipperås study site.
Scope of activities and main results
Kaj Ahlbom[1], Jan-Erik Andersson[2], Peter Andersson[2], Tomas Ittner[2], Christer Ljunggren[3], Sven Tirén[2]
[1]Conterra AB
[2]Geosigma AB
[3]Renco AB
September 1992

TR 92-23
Bedrock stability in Southeastern Sweden. Evidence from fracturing in the Ordovician limestones of Northern Öland
Alan Geoffrey Milnes[1], David G Gee[2]
[1]Geological and Environmental Assessments (GEA), Zürich, Switzerland
[2]Geologiska Institutionen, Lund, Sweden
September 1992

TR 92-24
Plan 92
Costs for management of the radioactive waste from nuclear power production
Swedish Nuclear Fuel and Waste Management Co
June 1992

TR 92-25
Gabbro as a host rock for a nuclear waste repository
Kaj Ahlbom[1], Bengt Leijon[1], Magnus Liedholm[2], John Smellie[1]
[1]Conterra AB
[2]VBB VIAK
September 1992

TR 92-26
Copper canisters for nuclear high level waste disposal. Corrosion aspects
Lars Werme, Patrik Sellin, Nils Kjellbert
Swedish Nuclear Fuel and Waste Management Co, Stockholm, Sweden
October 1992

TR 92-27
Thermo-mechanical FE-analysis of butt-welding of a Cu-Fe canister for spent nuclear fuel
B L Josefson[1], L Karlsson[2], L-E Lindgren[2], M Jonsson[2]
[1]Chalmers University of Technology, Göteborg, Sweden
[2]Division of Computer Aided Design, Luleå University of Technology, Luleå, Sweden
October 1992

TR 92-28
A rock mechanics study of Fracture Zone 2 at the Finnsjön site
Bengt Leijon[1], Christer Ljunggren[2]
[1]Conterra AB
[2]Renco AB
January 1992

TR 92-29
Release calculations in a repository of the very long tunnel type
L Romero, L Moreno, I Neretnieks
Department of Chemical Engineering,
Royal Institute of Technology, Stockholm, Sweden
November 1992

TR 92-30
Interaction between rock, bentonite buffer and canister. FEM calculations of some mechanical effects on the canister in different disposal concepts
Lennart Börgesson
Clay Technology AB, Lund Sweden
July 1992

TR 92-31
The Äspö Hard Rock Laboratory: Final evaluation of the hydro-geochemical pre-investigations in relation to existing geologic and hydraulic conditions
John Smellie[1], Marcus Laaksoharju[2]
[1]Conterra AB, Uppsala, Sweden
[2]GeoPoint AB, Stockholm, Sweden
November 1992

TR 92-32
Äspö Hard Rock Laboratory: Evaluation of the combined longterm pumping and tracer test (LPT2) in borehole KAS06
Ingvar Rhén[1] (ed.), Urban Svensson[2] (ed.), Jan-Erik Andersson[3], Peter Andersson[3], Carl-Olof Eriksson[3], Erik Gustafsson[3], Thomas Ittner[3], Rune Nordqvist[3]
[1]VBB VIAK AB
[2]Computer-aided Fluid Engineering
[3]Geosigma AB
November 1992

TR 92-33
Finnsjö Study site. Scope of activities and main results
Kaj Ahlbom[1], Jan-Erik Andersson[2], Peter Andersson[2], Thomas Ittner[2], Christer Ljunggren[3], Sven Tirén[2]
[1]Conterra AB
[2]Geosigma AB
[3]Renco AB
December 1992

TR 92-34
Sensitivity study of rock mass response to glaciation at Finnsjön, Central Sweden
Jan Israelsson[1], Lars Rosengren[1], Ove Stephansson[2]
[1]Itasca Geomekanik AB, Falun, Sweden
[2]Royal Institute of Technology,
Dept. of Engineering Geology, Stockholm, Sweden
November 1992

TR 92-35
Calibration and validation of a stochastic continuum model using the Finnsjön Dipole Tracer Test. A contribution to INTRAVAL Phase 2
Kung Chen Shan[1], Vladimir Cvetkovic[1], Anders Winberg[2]
[1]Royal Institute of Technology, Stockholm
[2]Conterra AB, Göteborg
December 1992

TR 92-36
Numerical simulation of double-packer tests in heterogeneous media
Sven Follin
Department of Engineering Geology, Lund University, Lund, Sweden
December 1992

TR 92-37
Thermodynamic modelling of bentonite-groundwater interaction and implications for near field chemistry in a repository for spent fuel
Hans Wanner, Paul Wersin, Nicolas Sierro
MBT Umwelttechnik AG, Zürich, Switzerland
November 1992

TR 92-38
Climatic changes and uplift patterns – past, present and future
S Björck, N-O Svensson
Department of Quaternary Geology,
University of Lund
November 1992

TR 92-39
Characterization of crystalline rocks in deep boreholes. The Kola, Krivoy Rog and Tyrnauz boreholes
NEDRA
December 1992

TR 92-40
PASS – Project on Alternative Systems Study. Performance assessment of bentonite clay barrier in three repository concepts: VDH, KBS-3 and VLH
Roland Pusch, Lennart Börgesson
Clay Technology AB, Lund
December 1992

TR 92-41
Buoyancy flow in fractured rock with a salt gradient in the groundwater. A second study of coupled salt and thermal buoyancy
Johan Claesson, Göran Hellström,
Thomas Probert
Depts. of Building Physics and Mathematical Physics, Lund University, Sweden
November 1992