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Project on Alternative Systems Study (PASS)
Final report

October 1992

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FOREWORD

R&D-Programme 86 and R&D-Programme 89 included studies of various alternative designs of deep repositories for spent nuclear fuel. The results of a comparison between the WP-Cave and KBS-3 systems have previously been published and are also reported in R&D-Programme 89.

The studies of other alternative concepts have been conducted during the past two years as an integrated project – PASS (Project Alternative System Studies). This project has now been completed and the results are presented in the present report.

For several years SKB has collaborated with the group of the Finnish electric power utilities that is responsible for management of waste from the Finnish nuclear power plants. Studies of different alternative concepts for deep repositories and for encapsulation of spent nuclear fuel have been conducted in collaboration with TVO. This has been done since 1991 within the framework of a special agreement on co-financing of certain sub-projects. A representive from TVO has been co-opted to the project group at SKB that has been in charge of the execution of PASS.

ABSTRACT (ENGLISH)

Alternative repository systems for deep disposal of spent fuel and different types of canisters are studied regarding technical aspects in Project on Alternative Systems Study (PASS). The objective is to present a ranking of repository systems as well as of canister types for each system.

The studies and compared systems are: KBS-3, Medium Long Tunnels (MLH), Long Tunnels (VLH) and Deep Boreholes (VDH). For KBS-3 and MLH five canister types are compared (copper/steel, copper/lead, copper (HIP), steel/lead and steel), for VLH two types (copper/steel and steel), and for VDH three types (titanium/concrete with non-consolidated fuel assemblies, titanium/concrete with consolidated assemblies, and copper (HIP) with non-consolidated assemblies).

The comparison is separated into three sub-comparisons (Technology, Long-term performance and safety, and Costs), which eventually are merged into one ranking.

With respect to canister alternatives the result is that the copper/steel canister is ranked first for KBS-3, MLH and VLH, while the tintanium/concrete canister is ranked first for VDH (non-consolidated as well as consolidated assemblies). With these canister alternatives the merged ranking of repository systems results in placing KBS-3 slightly in front of MLH. VLH comes thereafter and VDH last.

ABSTRACT (SWEDISH)

Alternativa system för djupförvaring av använt kärnbränsle och olika typer av kapslar studeras med avseende på tekniska aspekter i Projekt AlternativStudier för Slutförvar (PASS). Målet är att presentera en rangordning mellan systemen samt också för varje system en rangordning av alternativa kapseltyper.

De studerade och jämförda systemen är: KBS-3, Medellånga tunnlar (MLH), Långa tunnlar (VLH och Djupa borrhål (VDH). För KBS-3 och MLH har fem kapseltyper jämförts (koppar/stål, koppar/bly, koppar (HIP), stål/bly och stål), för VLH har två typer jämförts (koppar/stål och stål) och för VDH har tre typer jämförts (titan/betong med okonsoliderade bränsleelement, titan/betong med konsoliderade element samt koppar (HIP) med okonsoliderade element).

Jämförelserna delas upp på tre deljämförelser (Teknik, Långsiktig funktion och säkerhet samt Kostnader), vilka sammanvägs till ett slutligt omdöme.

I fråga om kapselalternativ är resultatet att koppar/stålkapseln placeras först för KBS-3, MLH och för VLH, medan för VDH titan/betong-kapseln förordas (okonsoliderade såväl som konsoliderade element). Med dessa kapselalternativ är resultatet av den sammanvägda rangordningen av systemen att KBS-3 placeras först, strax före MLH. Därefter kommer VLH och sist VDH.

SUMMARY

Besides the KBS-3 system, SKB has developed and analyzed the advantages and disadvantages of three alternative system designs:

- Deep Boreholes (Very Deep Holes = VDH): deposition at a depth of 2-4 km.
- Long Tunnels (Very Long Holes = VLH): deposition of relatively large canisters in horizontal tunnels. The tunnels can be several kilometres in length.
- Medium-Long Tunnels (Medium-Long Holes = MLH): deposition of canisters of same type as in KBS-3 in horizontal tunnels.

The sizes of the canister are different for the repository systems KBS-3/MLH, VDH and VLH. Different designs and materials have been developed and analyzed for all sizes.

The four repository systems (KBS-3, VDH, VLH and MLH) have been compared and ranked in the present study. The canister alternatives have also been ranked for each canister size.

The study has been conducted separately for three areas:

- Technology for canister fabrication and encapsulation (canister comparison) and for under ground construction and deposition (comparison of repository systems).
- Long-term performance and safety.
- Costs.

The canister alternatives were compared in the first round. The result was that the composite canister received the highest ranking for KBS-3/MLH and VLH. For VDH a concrete-filled titanium canister was recommended. These canister alternatives were then assumed in the comparison of the repository systems.

The comparison of the repository systems resulted in the following ranking:

1. KBS-3 and MLH
2. VLH
3. VDH

VDH came last in all three detailed comparisons and consequently last in the final ranking.

VLH was ranked in third place with regard to "Technology" but in second place (the same as KBS-3) with regard to "Costs". The comparison of "Long-term performance and safety" did not yield any decisive difference between KBS-3, MLH and VLH; all three systems were judged to be equivalent and were considered to meet very high safety standards. In the final ranking VLH therefore came in third place.

The outcome of the comparison between KBS-3 and MLH is not clear-cut. As regards "Technology", KBS-3 was judged to be more robust and more flexible in the deposition process. A strongly contributing reason is that the deposition of each canister is a closed, self-contained operation; it is regarded as a "parallel" process. In MLH the canister depositions are instead "series-connected". With regard to "Costs", however, there is a significant difference in the basic calculation to the advantage of MLH. Moreover, the economic optimization potentials for the two systems were judged to be equal. In the comparison between "Technology" and "Costs", the disadvantages displayed by MLH in the technology for deposition were judged to be crucial. The conclusion was that KBS-3 was ranked ahead of MLH.

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1 INTRODUCTION

The development of systems for encapsulation and final disposal of the long-lived waste from nuclear power plants was begun in Sweden in the mid-seventies. The work resulted during the period 1977 to 1983 in a series of reports that were gradually concentraded on encapsulation of the spent nuclear fuel in copper canisters and deposition (deployment) of these canisters at a depth of approximately 500 m in the Swedish bedrock. The resulting concept, KBS-3, was examined in detail by Swedish and foreign experts on behalf of the Swedish authorities. In 1984 the Swedish Government found that the system "in its entirety can be approved with regard to safety and radiation protection". With this approval, one of the requirements in the Act on Nuclear Activities was fulfilled for issuing fuelling permits for the Oskarshamn 3 and Forsmark 3 reactors. Since then the KBS-3 system has constituted the reference concept in the Swedish programme. The system is described in detail in /1-1/.

Since 1984, SKB has developed and evaluated several of the other interesting alternatives with successful results. It has been possible to show that these alternatives also have potential for meeting stringent safety requirements. Long-term safety potential has thus not proved to be a discriminating factor.

Between 1986 and 1989, the WP-Cave system was evaluated and compared with the KBS-3 system /1-2/. This system was then the one that had come the farthest in its development after KBS-3. The result was that the advantages of the KBS-3 design were found to outweigh those of WP-Cave.

Three other system designs have since been developed and analyzed in the following chronological order:

- Disposal of the spent fuel in boreholes at great depth, from 2 to 4 km below the ground surface. The system has been given the working name Deep Boreholes, or Very Deep Holes (VDH) /1-3/;
- Deposition of relatively large canisters in long horizontal tunnels. The system has been given the working name Long Tunnels, or Very Long Holes (VLH) /1-4/;
- Horizontal deposition in parallel tunnels of canisters of the same type as in KBS-3. The repository system has been given the working name Medium Long Tunnels, or Medium Long Holes (MLH). The design is described in Appendix 2.

Alternative canister designs exist for each different repository system.

Project Alternative System Studies (PASS, Projekt AlternativStudier för Slutförvar) was initiated for the twofold purpose of augmenting our understanding of significant aspects of the systems, and comparing the systems with the reference concept - KBS-3. The sole focus of the project has been to analyze and evaluate technical, safety-related and economic aspects. Other assessments of a general nature have not been made.

In the present report, the comparison procedure is described in chapter 4. The results obtained from the comparison of canister alternatives and the comparison of repository systems are presented in chapters 5 and 6.

The analysis of both canister alternatives and system alternatives has identified a large number of differences that have been discussed within the project. Only headings and sometimes a few comments are presented in this final report. For details the reader is referred to the background reports.

2 ANALYZED ALTERNATIVES

2.1 GENERAL

Four repository systems have been studied. For each of these, two or more canister designs have been considered. A brief presentation of the different repository designs and their canister alternatives is provided below. The principle of the repository designs is illustrated in Figure 2-1. Some of the canister alternatives are shown in Figure 2-2.

The different systems and their associated canister alternatives are described in Appendices 1 (KBS-3), 2 (MLH), 3 (VLH) and 4 (VDH). The descriptions primarily serve three purposes:

- to provide general information on layouts, canister designs, dimensions, weights, volumes etc., among other things as a basis for the detailed comparison of "Long-term performance and safety";
- to describe technology and equipment that have been considered by the project to comprise possible solutions for the respective systems and canister alternatives, and that have comprised the basis of evaluation for the detailed comparison of "Technology";
- to specify cost-influencing quantities, above all dimensions, for the detailed comparison of "Costs".

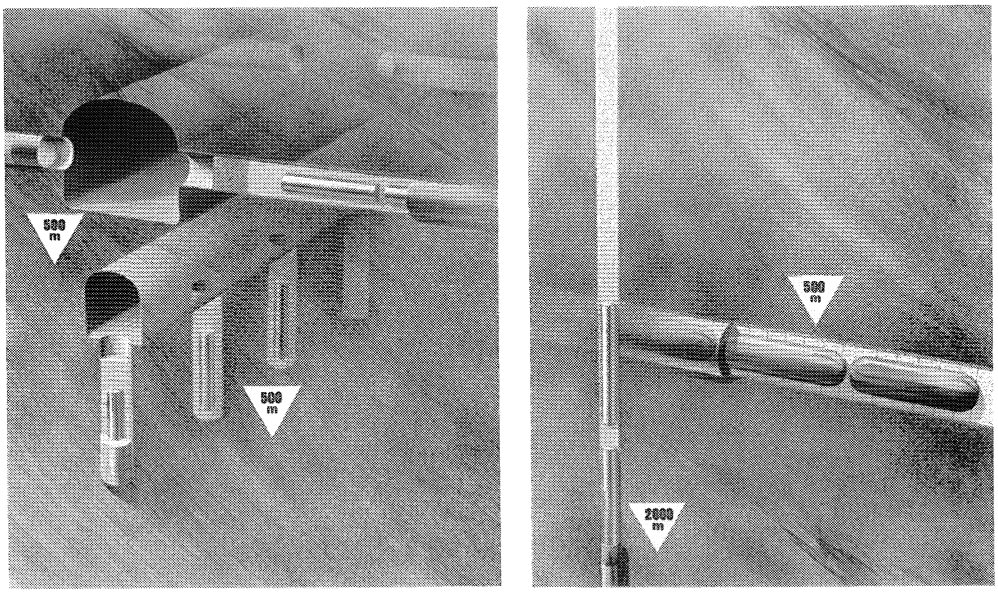
The descriptions do not claim to present optimized solutions. In several cases, for example, dimensions have been chosen so that the cost estimates could be based on similar premises. Methods have sometimes been defined in great detail so that no uncertainty could prevail regarding the premises of the comparisons. But changes should still be able to be made without this altering evaluations and judgements of the systems and the canister alternatives in the interim comparisons. The information given in the appendices shall be read and judged in this light.

2.2 KBS-3

The canisters are emplaced one by one in vertical bored holes in the floor of a deposition tunnel. The canisters are surrounded by highly compacted bentonite.

Canister alternatives

- Copper/steel canister (composite canister, designated by TVO "Advanced Cold Process, ACP").
- Copper/lead canister (filled with lead).
- Copper canister (Hot Isostatic Pressing, HIP).
- Steel/lead canister ("Gripsholm", filled with lead).
- Steel canister.



KBS-3 and Medium-long tunnels **Deep holes and Long tunnels**

Figure 2-1. *Alternative designs of the deep repository.*

2.3 MEDIUM-LONG TUNNELS - MLH (MEDIUM-LONG HOLES)

The canisters are emplaced in the centre of horizontal, bored tunnels and surrounded by highly compacted bentonite.

The canister alternatives are the same as for the KBS-3 system.

2.4 LONG TUNNELS - VLH (VERY LONG HOLES)

The canisters are emplaced in the centre of long, full-face-bored tunnels and surrounded by highly compacted bentonite.

Canister alternatives

- Copper/steel canister (composite canister design with hemispherical or flat ends).
- Steel canister (with hemispherical or flat ends).
- Copper canister (with hemispherical ends, not described in Appendix 3).

All the alternatives are self-supporting.

2.5 DEEP BOREHOLES - VERY DEEP HOLES (VDH)

The canisters are stacked on top of each other in deep holes (2–4 km) surrounded by a bentonite buffer.

Canister alternatives

- Titanium/concrete canister (filled with concrete).
- Copper canister (HIP).
- Titanium canister (self-supporting, not described in Appendix 4).

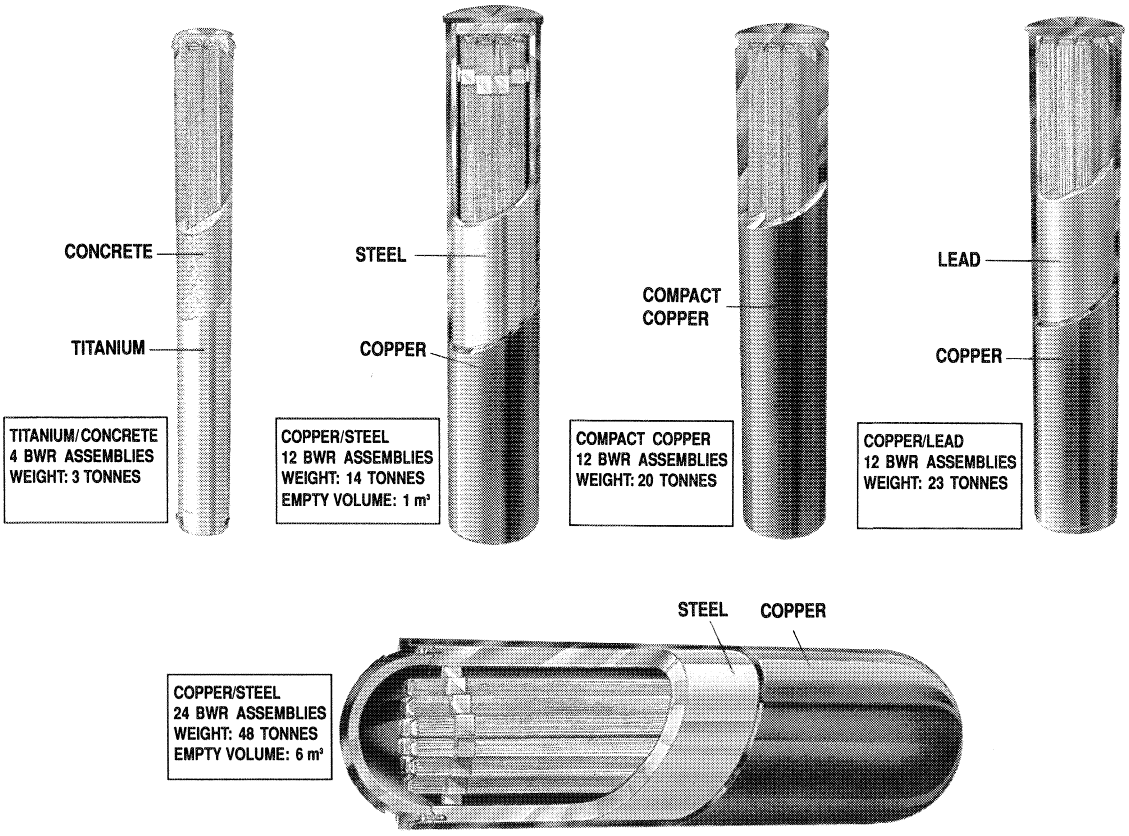


Figure 2-2. *Studied canister designs for the different alternative designs of the deep repository.*

3 GOALS

The goals of the comparisons are presented below and commented on with respect to what has been achieved in the project.

1) Ranking of studied repository systems according to logical method that takes into account identified, significant differences in the attributes of the various sytems. This goal has been the focus of the work. Strategy, evaluations and results are presented in this report.

2) Safety-related characterization of the alternative deep repository systems. The primary purpose was to be able to give an account of the safety potential of the studied systems, whether the systems could qualify for top ranking and thereby be considered as reference systems. VLH was analyzed in /3-1/.

Inasmuch as the project concluded in December 1991 /3-2/ that the VDH system could not qualify as the top-ranked system, no special safety assessment was ever begun for the VDH system.

4 RANKING METHODOLOGY

4.1 GENERAL

One problem in comparing alternative designs is the large number of differences that exist. Moreover, these differences are of varying importance. It is not possible to consider all of these differences at once and evaluate how the alternatives are to be ranked in relation to each other. A systematic approach is needed. In PASS, the work has been organized according to a hierarchical problem structure, which is described below.

4.2 HIERARCHICAL STRUCTURE USED IN THE COMPARISON

4.2.1 Problem structuring

The principle of the hierarchical structure is illustrated in Figure 4-1. At the top is the goal to be achieved and below it is a level with the elements that are included in the goal and that influence the choice. Each element can be subdivided into one or more lower levels.

At the base of the structure are the alternatives among which a choice is made to achieve the goal in the best way.

There are two hierarchical structures in PASS: one for ranking of the canister alternatives and one for ranking of the deep repository systems.

4.2.2 Goals

The main goals in PASS are "Canister for deep disposal of the spent nuclear fuel" (the canister comparison) and "System for deep disposal of the spent nuclear fuel" (comparison of deep repository systems).

Interim goals have also been defined, which are goals for interim comparisons and interim rankings of both canister alternatives and deep repository systems. The following three interim goals are distinguished:

- "Technology". The scope embraces methods and processes for producing the product (canister and deep disposal) with the quality required to achieve the necessary long-term performance.
- "Long-term performance and safety". The scope embraces stipulated requirements and criteria as well as the sensitivity of the performance of the different barriers to existing uncertaintites and to various events in the geological environment in the repository after sealing.
- "Costs". The scope embraces all aspects and factors that in principle distinguish the systems by the choice of cheaper or more expensive methods or equipment.

There are many methods for facilitating choices between alternatives in complex comparisons like the one in PASS. The above-described subdivision into "Technolo-

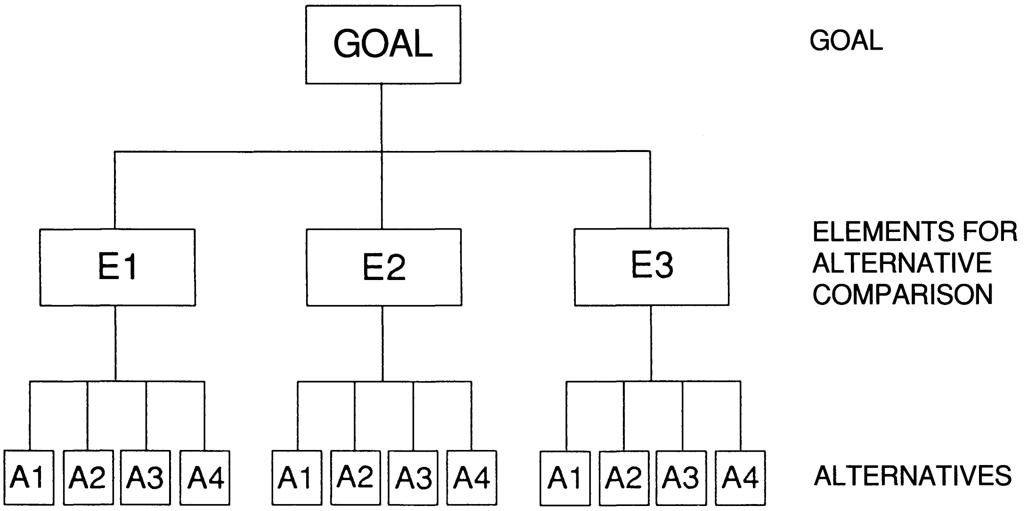


Figure 4-1. *Principle for hierarchical structuring.*

gy", "Long-term performance and safety" and "Costs" is based above all on the experience presented in /4-1/.

4.2.3 Hierarchical levels for the comparison

The interim comparison under "Technology" and "Long-term performance and safety" has been structured with different numbers of hierarchical levels. The structure used for the interim comparison of "Long-term performance and safety" with respect to canisters is illustrated by Figure 5-1 and with respect to repository systems by Figure 6-3. The structure used for the comparison of "Technology" with respect to canisters and repository systems is illustrated by Figures 5-2 and 6-1, respectively.

The interim comparison of "Costs" has been carried out with the aid of conventional cost calculations for the respective alternatives.

4.3 RANKING STEPS

In a first phase the canister alternatives for each repository system were ranked, after which the top-ranked canister alternatives were combined with the respective repository alternatives. These combinations were then compared and ranked in a second phase. As a result, the comparison of repository systems came to encompass only four alternatives.

As will be seen below, the canister comparison resulted in the same principle design for KBS-3, MLH and VLH, while for VDH the most economically advantageous alternative was given priority. This eliminated any differences in the premises as far as canister choice was concerned between the repository systems at a depth of about 500 m. The difference in canister choice between these systems and VDH is taken up in the discussion. (It is found not to have any influence on the outcome of the comparison between the repository systems.)

4.4 PREMISES IN THE COMPARISON

The point of departure was that the descriptions of KBS-3, VLH and VDH in the pertinent references /4-2, 4-3, 4-4/ have different purposes. The purpose in /4-2/ is to present a basis for cost calculations, so that the costs are not underestimated. The purpose in /4-3/ and /4-4/ is to explore the technical aspects and potential of the systems. An example is that VLH in /4-3/ has been designed with access via a steep ramp and not via shafts as in KBS-3 /4-2/. Another example is that the use of water-saturated bentonite is recommended in VLH in /4-3/, while PLAN 92 /4-2/ for KBS-3 assumes non-water-saturated bentonite (affects above all "Technology" and "Costs").

Where possible, similar premises have been assumed in PASS, so that "unnecessary" differences have been eliminated, even though this has meant in several cases that the reference design has been given parameters that are not optimal for the system. For the examples mentioned above, the solution was to choose ramp access and water-saturated bentonite in all three systems at 500 m depth.

Another difference in the premises is that VLH is described primarily as a long, extended repository /4-3/. However, it is also pointed out that VLH can be designed more compactly so that the deposition tunnels are made shorter, run parallel and be adapted to rock blocks in the same way as e.g. KBS-3. The rock block-adapted layout is evaluated in the discussion of the results of the comparison.

5 COMPARISON AND RANKING OF CANISTER ALTERNATIVES

5.1 COMPARED CANISTER ALTERNATIVES

5.1.1 General

Chapter 2 "ANALYZED ALTERNATIVES" mentions a number of different canister alternatives that are considered in PASS. In some cases it has been found on closer scrutiny that the alternative does not possess the qualifications assumed from the beginning. These alternatives have then been written off and have not been included in the final comparison, as will be seen below.

The difference between flat and hemispherical ends has not been analyzed in detail (applies to VLH). Alternatives that were originally presented in both versions have been regarded as one alternative in the study. This is merely a question of optimization without importance for the comparison in PASS.

5.1.2 KBS-3 and MLH

Both steel canisters and copper canisters of varying design have been analyzed for the repository systems KBS-3 and MLH. They are presented in Appendix 1 (B1).

The steel alternative is represented by two canister types:

- a self-supporting steel canister (Figure B1-6), and
- a thinner-walled steel canister (Figure B1-5), which is lead-filled to provide mechanical stability as well as an additional barrier function.

The copper alternative is represented by three canister designs:

- a copper/steel canister, consisting of an outer copper shell over an inner steel canister, which gives the structure mechanical stability (Figure B1-2a/b),
- a copper canister, which is lead-filled to provide the desired mechanical stability (Figures B1-3a/b),
- a solid copper canister, which is fabricated by means of hot isostatic pressing (HIP) of copper powder (Figures B1-4a/b).

5.1.3 VLH

This repository system, with deposition in full-face-bored tunnels, requires canisters of large diameter. Only self-supporting structures have been studied. A copper/steel canister with hemispherical ends is shown in figures B3-2a/b, and one with flat ends in B3-3 (Appendix 3). An alternative design is a steel canister without copper shell, as shown in the same figures.

Lead-filled canisters and HIP canisters have not been considered, since they have been deemed to be far too heavy to permit rational handling.

A self-supporting copper canister proved unable to resist creep deformation even if the walls are made uneconomically thick, so this type of canister was not included in the final comparison.

5.1.4 VDH

In this repository system, safety is based primarily on the rock's barrier function. Canister life plays a more subordinate role here compared with repositories at depths of about 500 m. Two canister materials have been analyzed:

Titanium canister with concrete fill, see Figure B4-2, with either intact fuel assemblies or consolidated fuel.

Solid copper canister fabricated by hot isostatic pressing (HIP) of copper powder.

New information from AECL, Canada /5-1/ has revealed that titanium has a poorer strength than was assumed in /5-2/. This means that a canister without inner support must be made of such thick material that the canister alternative is economically uninteresting.

A lead-filled titanium canister has no technical, safety-related or cost-related advantages over a concrete-filled titanium canister.

A self-supporting titanium canister and a lead-filled titanium canister have therefore not been included in the final comparison.

5.2 COMPARISON AND RANKING WITH REGARD TO "LONG-TERM PERFORMANCE AND SAFETY"

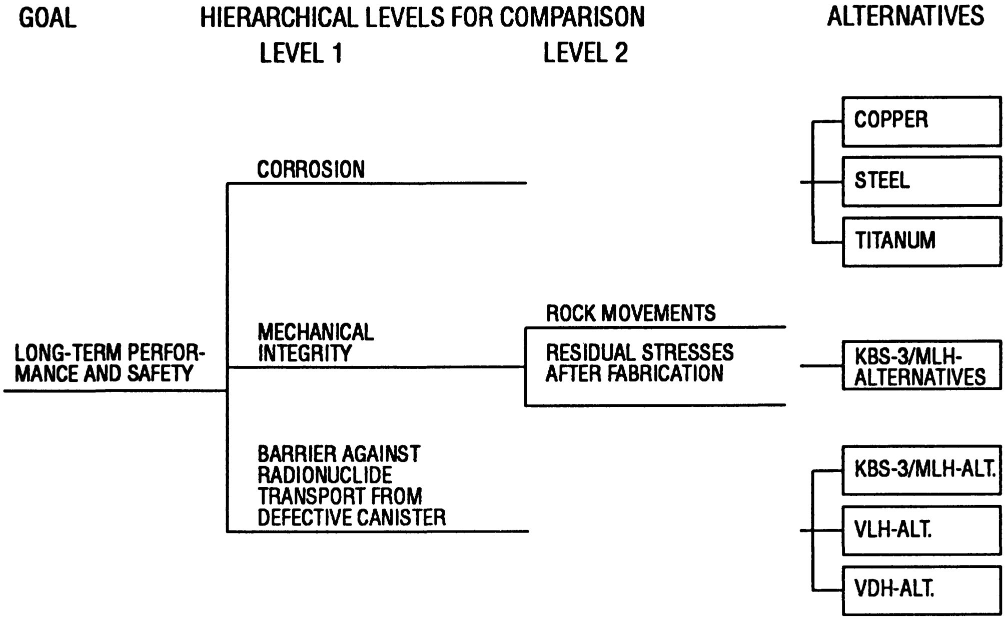


Figure 5-1. *Hierarchical structure for interim comparison of canister alternatives with respect to "Long-term performance and safety".*

5.2.1 General

The questions have been arranged according to the hierarchical principle described in chapter 4, "RANKING METHODOLOGY". The structure is illustrated in Figure 5-1.

5.2.2 Corrosion

The corrosion evaluation is essentially independent of repository design. For the systems KBS-3, MLH and VLH, the chemical environment in the repository is virtually identical, since the repository depth is the same, about 500 m. Knowledge of groundwater chemistry is very limited for great repository depths, such as in VDH. The information that is available indicates that the salinity of the water at these depths can be very high, up to 20% /5-3/. Moreover, the repository temperature is higher than in the other alternatives, 120oC to 150oC (depending on whether intact fuel assemblies or consolidated fuel is used /5-2/), compared with about 100oC.

Copper

KBS-3, MLH and VLH

A summary of the state of knowledge for copper corrosion has been compiled in /5-4/. The study confirms the conclusions from the KBS-3 report, i.e. that it has not been possible to identify any corrosion processes that could lead to canister penetration. A canister with a 50 mm thick copper shell will have a service life of several million years from the viewpoint of corrosion.

VDH

It has not been possible to fully investigate the copper canister for the VDH alternative, since the groundwater chemistry at depths of several kilometres is largely unknown. Several factors, such as high chloride concentrations and high temperatures, suggest that corrosion life at these depths can be reduced compared with corrosion life in a repository at a depth of about 500 m.

Steel

Steel is not, like copper, thermodynamically stable in water. A steel canister will therefore have a considerably shorter service life than a copper canister. This does not necessarily mean that a steel canister is unacceptable from a safety viewpoint. An analysis of pitting corrosion on steel has shown that the proposed steel canister would have an expected life of several thousand years /5-5/.

Some uncertainties remain for the steel alternative, however, in particular with regard to hydrogen gas evolution in conjunction with corrosion under reducing conditions and pressure build-up around the canister caused by the formation of corrosion products. The latter problem can be solved by giving the canister a thinner steel shell, which must then be supported mechanically. One proposal is that mechanical stability be achieved by lead filling. The corrosion resistance of the lead is incompletely understood, but it is believed that a lead-filled steel canister can isolate the fuel longer than a pure steel canister.

Titanium

Titanium is one of the main alternatives in the Canadian programme. Data and conclusions from the Canadian investigations are broadly applicable to the VDH alternative. The Canadian repository is assumed to have high chloride concentrations and high temperatures. Under these conditions, crevice corrosion on titanium is possible. Data and analyses carried out by AECL predict canister lives of 1 200 to

7 000 years /5-6/. Based on these analyses, a titanium canister in a VDH repository is estimated to have a service life of somewhere on the order of 1 000 years.

Conclusions – corrosion

Copper gives by far the longest canister life. In view of the long periods of time up to canister penetration, no relative ranking has been done among the different copper alternatives for KBS-3, MLH and VLH.

Despite the uncertainties in a repository environment for VDH, the HIP canister is judged to be preferable to the titanium canister from a corrosion point of view.

5.2.3 Mechanical integrity

During the last two years, questions pertaining to the mechanical integrity of the canister have been studied more closely by a group of five Swedish experts from industry and the academic world /5-7/. The questions investigated have mainly had to do with the effects on a canister of a rock displacement, residual stresses in copper canisters after sealing and creep deformation and creep relaxation of states of stress in the copper shell.

Rock movements

Modelling showed that rock movements of up to 100 mm will not pose any threat to the integrity of any of the canisters. The copper/steel canister was deformed the least, with a maximum strain in the copper shell of about 1%. The corresponding value for the HIP canister was about 4%. The lead-filled canister was not analyzed, but is judged to be more sensitive to deformation than the other two alternatives.

Residual stresses after fabrication

Residual stresses after sealing of the canisters have been calculated for both welded copper/steel canisters and for HIP canisters. When the canisters are sealed by welding, the maximum stress will lie in the range 70 MPa to 100 MPa, depending on the gap between the outer copper shell and the inner steel cylinder. For HIP canisters, the corresponding maximum value is about 90 MPa, but with a residual stress of about 50 MPa along the entire canister surface. The stresses are concentrated in the weld zone for the copper/steel alternative. In both of these cases, a considerable portion of the stresses will quickly relax due to creep deformation. The residual stresses for lead-filled canisters are deemed to be on comparable magnitude.

The stress levels for all canister alternatives studied are so low that there is no risk of creep fracture regardless of which copper grade is used.

Conclusions – mechanical integrity

The summarizing conclusion of the five experts was that the copper/steel canister was the most advantageous alternative among the copper canisters from a mechanical viewpoint.

5.2.4 Barrier performance against radionuclide transport from a defective canister

KBS-3 and MLH

In a normally functioning final repository with copper canisters or lead-filled steel canisters, no radionuclides will be transported out until after a very long period of time. The differences in barrier performance between these canisters will therefore only be of interest if one or more canisters are defective. The pure steel canister has a more limited life and therefore a clearly poorer barrier performance than the others.

In the scenario where one or more canisters are defective, the lead-filled copper canister provides comparatively better protection against the leakage of radionuclides. The lead filling itself is an effective barrier. If the copper shell should be defective, the lead offers virtually just as good corrosion protection. In the event groundwater should nevertheless reach some part of the fuel, the lead prevents leaching of the entire inventory at once, which potentially reduces the leakage of the gap and integranular inventory.

In the same scenario, the HIP canister has virtually the same properties as the lead-filled copper canister, but does not have two different materials as corrosion protection.

The composite canister is just as long-lived as the lead-filled copper canister and the HIP canister, but does not have the same potential to prevent leakage of radionuclides in the event of damage to the canister. If the outer copper canister should for some reason be penetrated, water will reach the inner steel canister, which will corrode. Swelling of the corrosion products can potentially worsen the defect in the copper shell. If the copper/steel canister is filled with water, all fuel rods in the canister will directly come into contact with water. In this case, however, the Zircaloy cladding will prevent the entire fuel inventory from being leached simultaneously. This scenario also poses a potential problem involving slow gas formation due to the reaction between water and steel. This problem requires further study.

Very little work has been done to evaluate the ability of a defective lead-filled steel canister to prevent leakage of radionuclides. As mentioned previously, lead is very resistant to corrosion under reducing conditions, which are guaranteed by the steel shell. The corrosion life of the canister is therefore most closely comparable to the copper alternatives. The steel, on the other hand, has little barrier effect in itself. The steel can cause problems with gas formation. On the other hand, the corrosion products are not expected to cause any problems in view of the thin wall thickness.

The pure steel canister has a limited service life (1 000 – 10 000 years), which means that all canisters will eventually leak simultaneously. This makes the safety margins for this canister considerably smaller than for the others.

VLH

The conditions for the copper/steel canister and the steel canister are equivalent to those for the equivalent alternatives in KBS-3/MLH.

VDH

The conditions during deposition are such that it is not deemed possible to guarantee that the canisters will be intact after deposition. There is no difference in this respect between the canister alternatives, which means that both the concrete-filled titanium canister and the HIP canister are regarded as equivalent with respect to their barrier performance against radionuclide transport.

5.2.5 Ranking – "Long-term performance and safety"

KBS-3 and MLH

All copper canisters and the lead-filled steel canister meet very stringent safety requirements with respect to corrosion and protection against radionuclide transport in the event of a defective canister. The difference between the copper alternatives is their performance in the event of defects. Since the probability of a through defect that allows water to enter the copper shell is very small, the alternatives are judged to be equivalent in the aforementioned respects. From a mechanical point of view, the copper/steel canister is judged to be the most advantageous alternative of the copper canisters.

Taken together, the differences between the different copper canisters are deemed not to be significant; all the alternatives are regarded as equivalent with regard to "Long-term performance and safety". The self-supporting steel canister is ranked after these.

The lead-filled steel canister has received far too little study to be ranked.

The ranking is summarized in Table 5-1.

Table 5-1. Ranking of studied canister alternatives for KBS-3 and MLH with respect to the interim comparison "Long-term performance and safety". A ranking of 1 is the best.

CANISTER ALTERNATIVE	RANKING
Copper/steel	1
Copper/lead	1
HIP	1
Steel	4
Steel/lead	*

*cannot be ranked due to incomplete data.

VLH

Based on the same judgement grounds as for the KBS-3/MLH alternatives, the copper/steel alternative is recommended over the steel alternative.

VDH

The alternatives are judged to be equivalent in view of the uncertainty regarding damages during deposition.

5.3 COMPARISON AND RANKING WITH REGARD TO "TECHNOLOGY"

5.3.1 General

The structure followed by the interim comparison is shown by Figure 5-2.

The technology and costs for fabrication of the copper shell for the KBS-3, MLH and VLH canisters have been thoroughly investigated /5-8/. Other judgements are based on the best estimates that have been possible from the available data.

5.3.2 KBS-3 and MLH

Since steel is the most widely used of all engineering materials, methods for fabrication and sealing of steel canisters are well-known and proven. From a fabrication viewpoint, a pure steel canister is by far the most advantageous alternative.

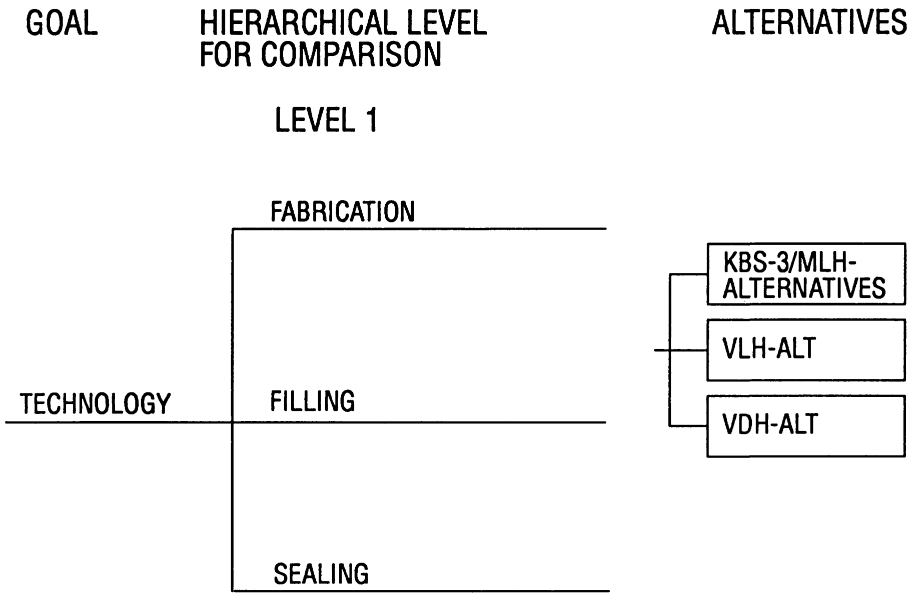


Figure 5-2. *Hierarchical structure for interim comparison of canister alternatives with respect to "Technology".*

Among the copper alternatives, fabrication of the canisters is by and large identical. In all cases the outer copper shell consists of an approx. 50 mm thick canister, which is given mechanical stability by means of an inner structure of steel, lead or isostatically pressed copper powder. The method for fabrication of the copper shell has not yet been determined, but it will be based on, among other things, considerations relating to weldability and detectability of defects by means of non-destructive testing and thus does not constitute a basis for relative ranking among the canister alternatives to any essential degree.

Encapsulation in a copper/steel canister is done without subjecting the canister and the fuel to elevated temperatures, except during the sealing procedure when a local heating of the top part of the canister takes place. Fabrication of the copper/steel canister requires that the inner surfaces of the copper shell be machined to the desired dimensions with relatively close tolerances. This is not necessary for the other alternatives.

Technology for lead filling has previously been studied on a model scale /5-9/. This study has been supplemented with a computer simulation of lead casting on a full scale /5-10/. The computer simulation shows that lead casting with control of the solidification process is possible by means of a combination of cooling and heating in sections along the copper canister. The study also shows that control of the process may be complicated. It will further require full-scale development work. Welding of a lead-filled canister, with the risk of remelting of the lead, can also prove to be more difficult to control than welding of a copper/steel canister.

Hot isostatic pressing of copper powder is a process that takes place under high pressures and temperatures in a hot-cell environment. The process also leads to a canister from which it is very difficult, if not impossible, to retrieve the fuel. As has been shown previously, the purity requirements on the copper powder are high if isostatic pressing is to produce copper with mechanical properties equivalent to those of the copper in the outer shell /5-11/. This will probably require handling of the copper powder in a non-oxidizing atmosphere /5-12/. The possibility can therefore not be ruled out that an encapsulation plant for hot isostatic pressing of canisters must contain on-site atomizing equipment.

The same fundamental difficulties present themselves for a lead-filled steel canister as for the lead-filled copper canister. However, the lead filling process may turn out to be easier to control if the outer shell is of steel, since steel has a lower thermal conductivity than copper. The canister's lid does not need to be welded, which facilitates fabrication considerably.

5.3.3 VLH

The situation for VLH is very similar to the KBS-3 and MLH systems. A pure steel canister is the simplest alternative from the fabrication viewpoint. Only one type of copper canister, the copper/steel canister, has been considered.

5.3.4 VDH

From a technical viewpoint, the alternative with a concrete-filled titanium canister and intact fuel assemblies is the simplest alternative. If consolidated fuel is to be used, the encapsulation plant must be supplemented with equipment for dismantling of fuel assemblies.

For a hot isostatically pressed copper canister, the same considerations apply as were discussed under section 5.3.2, **KBS and MLH.**

5.3.5 Ranking - "Technology"

KBS-3 and MLH

From the fabrication viewpoint, a pure steel canister is the most favourable alternative for KBS-3 and MLH (as well as VLH).

Among the alternative copper canisters, the copper/steel canister is ranked first. Even though further development work remains to be done as far as sealing and non-destructive testing are concerned, the technology is largely known and established. Lead casting entails the need for yet another process in the encapsulation plant and requires subjecting the spent fuel to elevated temperature. The alternative hot isostatic pressing is ranked lowest in view of the requirements on high pressure, high temperature and high-purity copper and the difficulties of repairing defective canisters and retrieving fuel.

The ranking is presented in Table 5-2.

Table 5-2. Ranking of studied canister alternatives for KBS-3 and MLH with respect to the interim comparison "Technology". A ranking of 1 is the best.

CANISTER ALTERNATIVE	RANKING
Copper/steel	2
Copper/lead	4
HIP	5
Steel	1
Steel/lead	2

VLH

For the same reasons as those given for the KBS-3 and MLH alternatives, the pure steel canister is ranked ahead of the copper/steel canister.

VDH

For VDH, a concrete-filled titanium canister for the entire fuel assembly is the simplest alternative from a technical viewpoint. Consolidation of fuel entails yet another step in the encapsulation process, and the same difficulties exist for hot isostatic processing as mentioned above.

5.4 COMPARISON AND RANKING WITH REGARD TO "COSTS"

5.4.1 General

The cost comparison has been done only for those cost items included under "Encapsulation station" in /5-13/, which include investment, operating and decommissioning costs. Weight and size differences between the canister alternatives (for the same repository system) do not lead to any significant cost differences in other parts of the facility (industrial area and deep repository).

The cost calculation work has been based on the calculation in /5-13/ (the KBS-3 system with lead-filled copper canister). The items that are changed have been added or subtracted. The costs for fabrication of canisters are more uncertain than other costs in the calculation, since they have to a large extent only been estimated in relation to the cost in /5-13/.

The costs have been distributed in time to enable the present value to be calculated. The operating period has been set at 20 years regardless of repository system or canister alternative.

5.4.2 Costs

KBS-3 and MLH

The calculated costs are shown in Table 5-3.

Table 5-3. Summary of calculated costs for encapsulation plant for KBS-3/MLH canisters; the total sum and the present value as per January 1992 for a discount rate of 2.5 %

CANISTER ALTERNATIVE	TOTAL COST MSEK	COMP. FACTOR	PRESENT VALUE 2.5% MSEK	COMP. FACTOR
Copper/steel	6 800	1.31	3 050	1.24
Copper/lead	6 800	1.31	3 100	1.27
HIP	6 100	1.17	2 800	1.14
Steel	5 400	1.04	2 500	1.02
Steel/lead	5 200	1.00	2 450	1.00

Table 5-3 shows that the two steel alternatives have roughly the same cost and are the cheapest. The copper alternatives copper/steel and copper/lead, which are also equivalent from a cost viewpoint, are the most expensive. The HIP alternative takes an intermediate position.

It may be surprising that the steel/lead canister is not more expensive than the pure steel canister, but the explanation is that the steel shell in the steel/lead canister is a commercial tube product that is available at a low cost. Lead has a moderate cost per tonne.

The copper alternatives are the most expensive, as expected. HIP is the cheapest of them, which is explained by the fact that only a thin-walled copper container is needed (copper powder fills out the empty volume prior to pressing).

This order among the alternatives takes into account the uncertainties associated with the costs for the empty canisters.

The ranking is shown in Table 5.4.

Table 5-4. Ranking of studied canister alternatives for KBS-3 and MLH with respect to the interim comparison "Costs". A ranking of 1 is the best.

CANISTER ALTERNATIVE	RANKING
Copper/steel	4
Copper/lead	4
HIP	3
Steel	1
Steel/lead	1

VLH

The calculated costs are shown in Table 5-5.

Table 5-5. Summary of calculated costs for encapsulation plant for VLH canisters; the total sum and the present value as per January 1992 for a discount rate of 2.5%

CANISTER ALTERNATIVE	TOTAL COST FACTOR MSEK	COMP. VALUE 2.5%	PRESENT FACTOR SEK	COMP.
Copper/steel	8 800	1.17	3 850	1.15
Steel	7 500	1.00	3 350	1.00

The difference between the copper/steel design and the pure steel canister is about 15%, which is less than the difference between the corresponding canister alternatives for KBS-3/MLH.

VDH

The calculated costs are shown in table 5-6.

Table 5-6. Summary of calculated costs for encapsulation plant for VDH canisters; the total sum and the present value as per January 1992 for a discount rate of 2.5 %

CANISTER ALTERNATIVE	TOTAL COST MSEK	COMP. FACTOR	PRESENT VALUE 2.5% MSEK	COMP. FACTOR
Concrete-filled titanium, non-consolidated assemblies	7 000	1.00	3 150	1.00
Concrete-filled titanium, consol. assemblies	7 100	1.01	3 350	1.06
HIP, non-consol. assemblies	6 900	0.97	3 300	1.05

The total cost is roughly the same for all the alternatives while the present value is lowest for the concrete-filled titanium canister with non-consolidated fuel assemblies.

It is noteworthy that the costs (present value) are slightly more favourable for encapsulation of non-consolidated assemblies than for encapsulation of consolidated assemblies, despite the fact that the number of canisters is twice as great.

5.5 RANKING OF CANISTERS

5.5.1 KBS-3 and MLH

The results of the interim comparisons with respect to "Long-term performance and safety", "Technology" and "Costs" are summarized in Table 5-7.

Table 5-7. Summary of results from the three interim comparisons of canister alternatives for KBS-3 and MLH. A ranking of 1 is the best.

CANISTER ALTERNATIVE	LONG-TERM PERFORMANCE AND SAFETY	TECHNOLOGY	COSTS
Copper/steel	1	2	4
Copper/lead	1	4	4
HIP	1	5	3
Steel	4	1	1
Steel/lead	*	2	1

* cannot be ranked due to incomplete data.

A weighing-together of the results of the three interim comparisons has led to the copper canisters being ranked ahead of the pure steel canister in view of the difference in corrosion resistance. A pure steel canister has a much shorter lifetime, and in light of the safety-related consequences of this, this alternative has been judged unsuitable.

The lead-filled steel canister has not been fully investigated as far as the corrosion resistance of the lead and the mechanical strength of the canister are concerned. As a result, this canister alternative cannot be ranked with respect to "Long-term performance and safety".

Among the copper alternatives, the copper/steel canister has been ranked ahead of the lead-filled canister, partly for fabrication-related reasons and partly in view of the assessment of the mechanical integrity of the canister. Due to fabrication-related reasons the isostatically pressed canister is deemed troublesome.

The conclusion is that the copper/steel canister is ranked highest, followed by the copper/lead canister. The HIP canister and the steel canister are ranked after these.

5.5.2 VLH

A copper/steel canister is recommended for corrosion reasons. (Same assessment as for KBS-3 and MLH.)

5.5.3 VDH

A concrete-filled titanium canister is recommended. The same assessment is made for the copper alternative as for HIP canister for KBS-3/MLH.

6 COMPARISON AND RANKING OF DEEP REPOSITORY SYSTEMS

6.1 DEFINITION OF COMPARED SYSTEMS

For each studied system, a reference design has been chosen as a basis for the comparison between the systems. These reference designs are described in appendices 1-4 with the purposes given in chapter 2. Additional details are taken up where they are of importance for the analysis, especially for the cost comparison.

The combination of repository system and canister alternative in each reference design is a consequence of the outcome of the ranking of canisters in chapter 5. The combinations are:

- KBS-3 with copper/steel canister as per Figure B1-2a in Appendix 1.
- MLH with copper/steel canister as per Figure B1-2a in Appendix 1.
- VLH with copper/steel canister as per Figure B3-2a in Appendix 3.
- VDH with concrete-filled titanium canister as per Figure B4-2 in Appendix 4.

By including the copper/steel canister in all the three systems at 500 m depth, differences that would otherwise result solely from the properties and performances of the canisters are avoided. The possibility of replacing the copper/steel canister in KBS-3 and MLH with a lead-filled copper canister is taken up for special discussion in those contexts where this flexibility is of importance.

The choice of a concrete-filled titanium canister for VDH means that the cheapest alternative is included in the comparison.

6.2 COMPARISON AND RANKING WITH REGARD TO "TECHNOLOGY"

6.2.1 General

The analysis has been carried out in two stages:

Stage 1: The work entailed subdividing the questions into levels according to the hierarchical pattern presented in chapter 4, and carrying out a comparison with notation of advantages and disadvantages. This was carried out by a lone investigator, which meant that the discussion of the results came to be coloured in part by just how objective the reported judgements could be assumed to be. The structure of the questions was taken as a basis for the ranking work in Stage 2.

Stage 2: In this stage a comparison was made with the aid of an "Expert Judgement". The expert group that was appointed consisted of six persons (four associated with SKB and two associated with TVO). In an initial phase, the experts examined the individual questions and the hierarchical structuring. This resulted in a revised version. Each one then carried out a pairwise comparison of elements and alternatives. The method is described in brief in Appendix 5. All of Stage 2, including the evaluation, is presented in /6-1/.

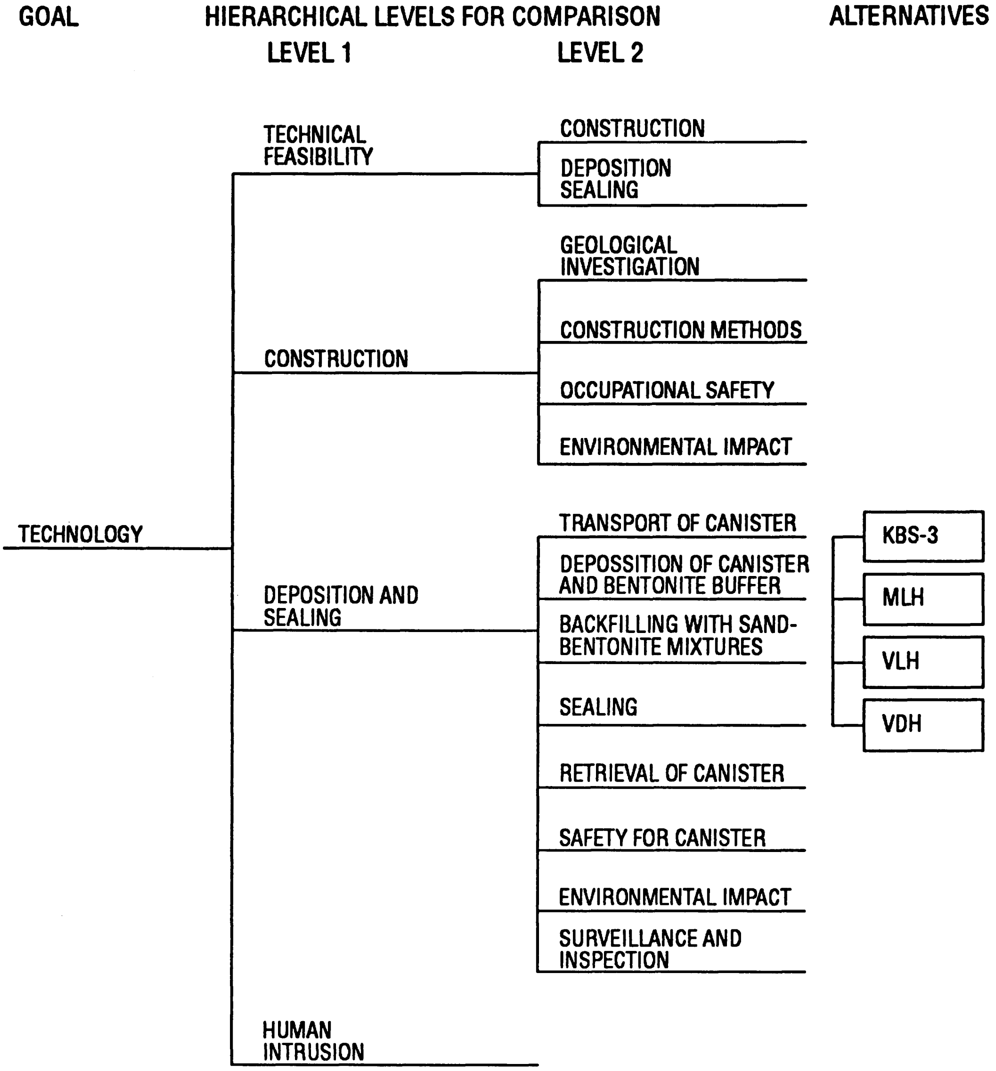


Figure 6-1. *Hierarchical structure for "Technology".*

6.2.2 Hierarchical structure in Stage 2

The hierarchical structuring of the questions is illustrated by Figure 6-1, and Appendix 6. The elements on level 1 consist of the following, to some extent chronologically logical, steps:

- Technical feasibility.
- Construction.
- Deposition and sealing.
- Human intrusion (after sealing).

These in turn are subdivided on a lower level, level 2. Appendix 6 shows that the subdivision was done on yet another level, level 3.

6.2.3 Guidelines for the expert group

Explanations of each element and their subdivision into sublevels were given to the experts as a basis for the pairwise comparison. A complete subdivision on all levels, along with some of the explanatory comments, is given in Appendix 6.

6.2.4 Results of "Expert Judgement"

The evaluated and compiled results of the expert judgement are presented in Table 6-1. A more detailed account of the results is given in Appendix 7 and /6-1/.

Table 6-1. Results of "Expert Judgement" for "Technology".

SYSTEM	WEIGHT TO ACHIEVE THE GOAL "TECHNOLOGY" MEAN VALUE FOR GROUP	RANKING
KBS-3	0.39	1
MLH	0.27	2
VLH	0.19	3
VDH	0.15	4
Total	1.00	

The weights in Table 6-1 are arithmetic means of the ratings of the six experts. The pairwise comparison is based on assessments of differences with ratings between 1 and 9, plus a weighing-together of the ratings into subweights in relation to the goal, see the description of the principles in Appendix 5. The subweights are obtained in a ratio scale.

As evident from Appendix 7, all 6 experts have the same ranking as in Table 6-1, with some variation in the subweights for the different repository systems in relation to the goal "Technology".

6.2.5 Discussion

The result is clear in terms of which alternative is ranked highest. But could this be due to the fact that the experts subconsciously favoured the most "established" system? This question was taken up in a subsequent group discussion with the experts. The conclusion was that there are well-founded reasons for each expert's judgement that explain why KBS-3 was recommended.

The group felt that the foremost merit of KBS-3 was the fact that the deposition of each canister constitutes a closed, self-contained process, while the other systems entail a certain interdependence or serial connection in the deposition procedure between each canister and the following canister. The group also felt that this entails a greater flexibility for KBS-3 than for the other three systems.

The main reason VDH was ranked last is the difficulties associated with the deposition procedure. The experts are uncertain how these problems should be solved in order to meet the quality requirements.

The group's opinions regarding the differences between MLH and VLH cannot be identified on the basis of the available material.

6.2.6 Ranking – "Technology"

In accordance with the outcome as it is presented in Table 6-1, the ranking for "Technology" is given in Table 6-2.

Table 6-2. Ranking of studied systems with respect to the interim comparison "Technology". A ranking of 1 is the best.

SYSTEM	RANKING
KBS-3	1
MLH	2
VLH	3
VDH	4

6.3 COMPARISON AND RANKING WITH REGARD TO "LONG-TERM PERFORMANCE AND SAFETY"

6.3.1 General

The development of the different repository systems has resulted in designs all of which are judged to have potential for meeting stringent requirements on long-term performance and safety. The comparison and ranking in this chapter are based on this judgement.

The analysis is based on qualitative comparisons aimed at the goal of describing differences between the different repository systems. These assessments serve as a basis for the final ranking.

In comparison with the two stages carried out with regard to "Technology" (see section 6.2.1), the analysis here corresponds to Stage 1. The difference, however, is that the final result here is based on only a few simple evaluations, which makes the reasons for the ranking clearer.

The background material for comparison and ranking of the repository systems with regard to long-term performance and safety is presented in /6-2/ and /6-3/.

6.3.2 Analysis sequence

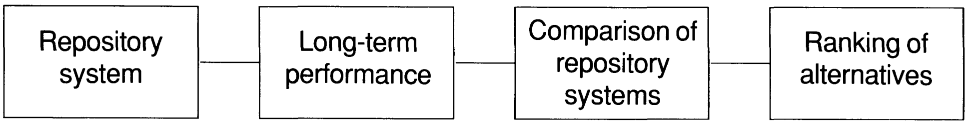
The analysis has been carried out in steps as illustrated by the scheme in Figure 6-2.

In the first step, the characteristic properties of each repository system that are of importance for the analysis were defined.

The long-term performance of the systems and the different barriers was then clarified. The descriptions were based on the reference scenario used in the SKB-91 assessment /6-4/. In addition, the effects of the glaciation scenario and the "human intrusion" scenario (after sealing) were analyzed.

The comparison of the repository systems was based on the performance of the individual barriers in the different repository systems as well as the performance of the integrated system. The comparison of the individual barriers follows the traditional subdivision in safety assessments: near field (canister, bentonite buffer, rock in near field), far field (rock in far field), and biosphere.

The comparison of the performance of the integrated system was based on differences with regard to:



Figur 6-2. *Analysis sequence for comparison and ranking with regard to "Long-term performance and safety".*

- estimated doses,
- possibility of validation,
- robustness of the barriers (multibarrier principle),
- sensitivity for rare events and extreme events.

In the final ranking of the systems, an analysis was made of whether there are any differences of importance for long-term safety in the performance of individual barriers or the entire repository system.

6.3.3 Comparison of individual barriers

The comparison has followed the structure illustrated in Figure 6-3.

Generally speaking, there are many characteristic properties and technical factors that influence the properties that are of importance for the evaluation of a system's long-term performance and safety. It has therefore been important to systematically go through them and see what differences are of importance for the comparison. The result was that only a few were judged to be of possible importance. These are presented in Table 6-3 and discussed below. By far most of the differences are believed not to affect the ranking between the repository systems. The entire analysis is reported in /6-3/.

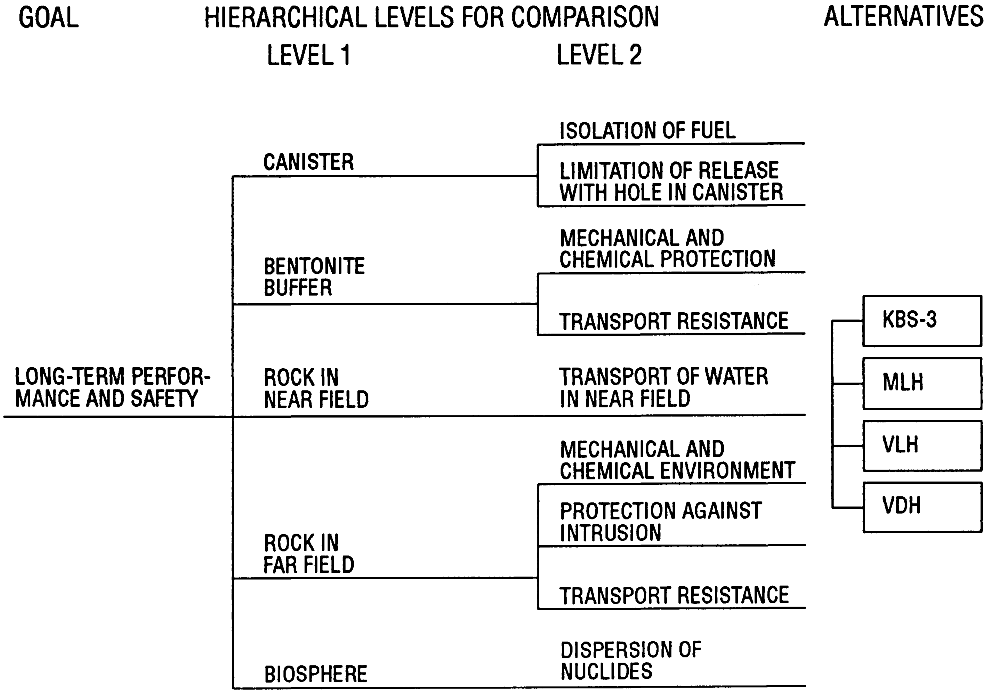


Figure 6-3. *Analysis scheme for "Long-term performance and safety".*

Table 6-3. Identified most important differences pertaining to nuclide transport from defective canisters after sealing of the repository. The comparison is done with KBS-3 as the norm. "o" means no difference, "+" means advantage and "-" disadvantage. The comparison applies to the reference designs and canister alternatives described in section 6.1.

ACTIVITY	MLH	VLH	VDH	COMMENT
Trpt. in canister	–	–	(–)	Lies horizontal VLH more fuel/canister VDH has potentially earlier release
Trpt. in bentonite	–	–	–	Shorter trpt. pathway, no bentonite/sand as in KBS-3
Trpt. in dist. zone	+	+	(+)	Dep. tunnel in KBS-3 disadvantage
Trpt. in far field	o	-	+	VLH in contact with more regional fracture zones. Longer pathway in VDH and potential barrier in saline groundwater.
Biosphere	o	+	+	Greater potential dilution for VLH and VDH

Canister

The term "canister" includes both the canister shell and any inner fill.

The main function of the canister is to isolate the fuel from its surroundings for a long period of time. The length of this time is an essential parameter in the assessment of long-term safety.

Potential differences in canister life

Canister life is determined by the properties of the canister and the surrounding bentonite buffer.

The conclusion is that there is no significant difference in canister life between KBS-3 and MLH (copper/steel canister) on the one hand and VLH (copper/steel canister) on the other, assuming that the canisters are identical in terms of material choice and that the surrounding chemical environment is equivalent - only the size of the canister distinguishes them noticeably.

The life of the VDH canister is, on the other hand, judged to be shorter than that of the other systems, see chapter 5.

Potential difference in nuclide release from canister

The shorter life of the VDH canister, in combination with the greater risk of damages to the canister during deposition, leads to a potentially earlier release from the VDH system and consequently a greater release of, above all, non-sorbing nuclides.

Furthermore, it has been concluded that a horizontal orientation of the canister (MLH and VLH) is associated with a risk of greater releases than a vertical orientation (upright canister KBS-3 and VDH) /6-3/. The reason is that a presumptive hole in a horizontal canister (most probable in the weld) could end up at the bottom of the canister, allowing a larger quantity of contaminated water in the canister to be expelled by gas. In a vertical, upright canister the weld will be at the top, and a hole there is not associated with the same gas problem. Here there is also a possibility that the gas can limit the transport of radionuclides.

The evaluation shows that a presumptive canister defect renders more fuel accessible in VLH than in KBS-3 and MLH.

Bentonite buffer

Bentonite buffer refers here only to the buffer placed around the canister itself. Its function is to:

- minimize the water flow around the canister (counteract in-transport of corrosive species dissolved in the groundwater and out-transport of dissolved radionuclides from a defective canister),
- provide mechanical protection for the canister against possible displacements in the rock,
- reduce and delay radionuclide transport through sorption.

The bentonite material has properties that have certain given consequences. The ones of technical importance are:

- certain given chemical environment in terms of pH etc.,
- self-healing effect in the event of movements in the buffer,
- swelling and penetration in fractures in the rock walls of the deposition hole.

Potential differences in the buffer's mechanical and chemical protection

The technical aspects of emplacing the bentonite buffer were included in the assessment under "Technology" in section 6.2. Differences in long-term properties of the bentonite buffer between KBS-3 and VLH have been analyzed in /6-2/ for a number of different premises that could lead to a deterioration of the properties of the bentonite. The processes of transformation to hydrous mica and cementation in the buffer can lead to an increase in hydraulic conductivity and a decrease in swelling capacity. However, the properties can be altered substantially without this having any serious consequences for long-term safety, although the robustness of the buffer function is affected. But the transport mechanism through the bentonite is still diffusion. It is only if severe displacements take place in the rock that the aforementioned deterioration of buffer properties can impair safety. In this case, the clay is not able to swell into fractures that have opened in the rock and seal them, nor is it self-healing.

Since it is assumed that the same material quality will be used for all systems, the geochemical environment in KBS-3, MLH and VLH is equivalent with regard to the risk of contamination with impurities during the homogenization phase and the risk of bentonite transformation in the long-term perspective. Nor is any difference considered to exist as a consequence of vertical or horizontal orientation of the canister; the bentonite bears an upright canister, as shown in the Stripa experiment /6-5/, and should consequently also bear a horizontal canister.

There is a greater risk of undesirable changes for VDH. The temperature in the deposition zone is high and the groundwater has a high salinity. In addition there is uncertainty as to the question of the quality of the bentonite after deposition. There is a risk of uneven impermeability, at the same time as the planned impermeability of the bentonite is lower than for systems at 500 m depth. Of necessity, the thickness of the buffer will also be significantly less in VDH than in other systems, as will resistance to in-transport of corrodants.

Potential differences in radionuclide release from the bentonite buffer

The buffer's performance as a barrier against out-transport of nuclides is determined in the long-term perspective by its physical and chemical properties and its geometry. Possible transport pathways through the bentonite and the transport resistance in the buffer are evaluated in the comparison /6-3/.

Differences between the systems are based on the assumption that the bentonite buffer possesses the quality and the properties stipulated in the target specification for the buffer.

KBS-3 has a little advantage in that the deposition drift above the deposition hole has access to large quantities of sorbing materials. However, it can be concluded that the theoretical differences that exist between KBS-3, MLH and VLH do not lead to any significant difference with respect to the diffusive transport of radionuclides through the bentonite buffer.

For VDH, on the other hand, disadvantages have been identified in that the bentonite barrier possesses poorer transport resistance even under ideal conditions due to the deposition conditions.

Rock in near field

By this is meant in the comparison the rock mass near the repository's tunnels, deposition holes and rock caverns that is affected by the rock excavation procedure and thereby constitutes a "disturbed zone".

The disturbed zone possesses altered hydraulic conductivity and thereby possibly an increased potential for escape of radionuclides and ingress of corrosive species to the buffer /6-6/.

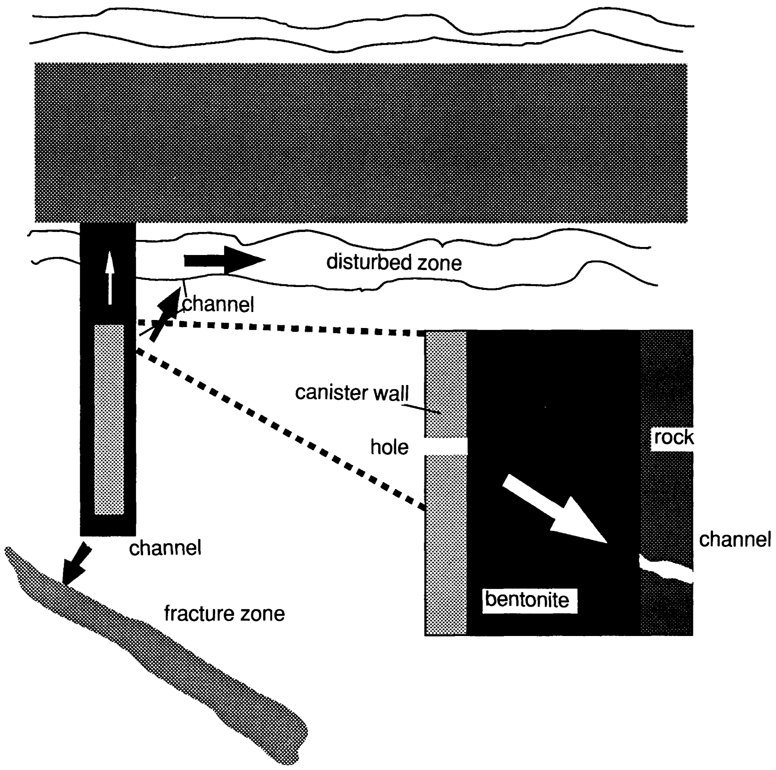


Figure 6-4. KBS-3. Transport pathways for radionuclides in the near field.

After deposition, the rock in the zone can be affected by the heat given off by the fuel, giving rise to effects on geochemistry, groundwater flow and mechanical stability of the rock.

Potential differences in radionuclide transport from the near field

A number of different transport pathways are possible in all the systems, provided that one or more canisters have lost their isolating capacity. The disturbed zone around the deposition hole (tunnel) is a probable transport pathway for radionuclides up to an intersecting fracture zone. Two processes have been analyzed:

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

Conceivable transport pathways for the different repository systems are presented in Figures 6-4 (KBS-3), 6-5 (MLH), 6-6 (VLH) and 6-7 (VDH) /6-3/:

<u>KBS-3 (see Figure 6-4)</u>

- Diffusion through the bentonite to the disturbed zone around the hole and in this zone, or in an intersecting fracture in the rock, to the disturbed zone around the deposition tunnel.
- Diffusion upwards in the bentonite in the deposition hole to the disturbed zone around the deposition tunnel.
- Diffusion upwards in the bentonite in the deposition hole to the backfilled deposition tunnel and further diffusion to the disturbed zone or directly to an intersecting fracture zone.
- Diffusion through the bentonite and the rock to a fracture zone in the vicinity of the deposition hole.

<u>MLH (see Figure 6-5)</u>

- Diffusion through the bentonite to the disturbed zone around the deposition tunnel and further to the disturbed zone around the side or central tunnel.
- Diffusion through the bentonite barrier to the disturbed zone or directly to a fracture zone that intersects the deposition tunnel.
- Diffusion through the bentonite and the rock to a fracture zone that does not intersect the deposition tunnel.

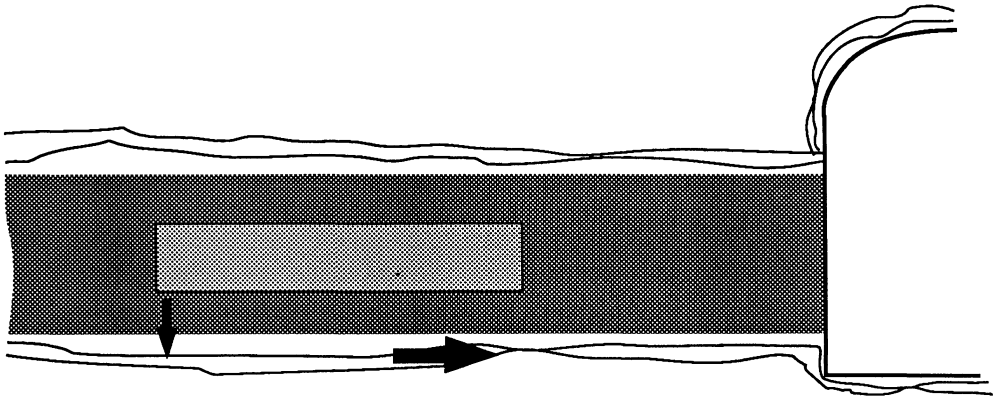


Figure 6-5. *MLH. Transport pathways for radionuclides in the near field.*

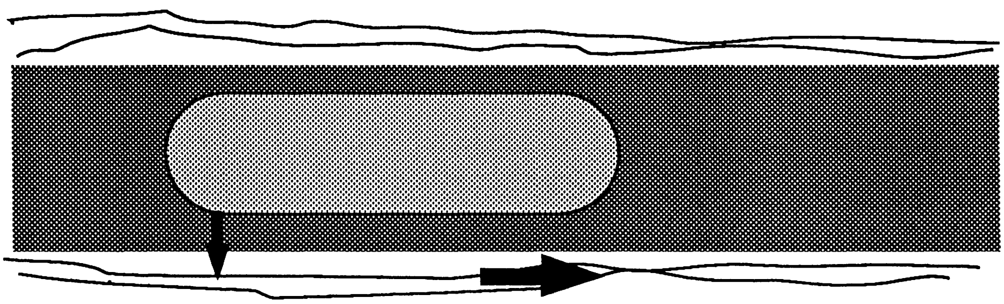


Figure 6-6. *VLH. Transport pathways for radionuclides in the near field.*

VLH (see Figure 6-6)

- Diffusion through the bentonite barrier to the disturbed zone or directly to a fracture zone that intersects the deposition tunnel.
- Diffusion through the bentonite and the rock to a fracture zone that does not intersect the deposition tunnel.

VDH (see Figure 6-7)

- Diffusion through the bentonite to the disturbed zone around the hole and in this zone, or in this zone to a fracture that intersects the deposition hole.
- Advection in the bentonite slurry in the deposition hole to an intersecting fracture zone.

The disturbed zone around the deposition hole and deposition tunnels can be an important channel for the radionuclide transport from the bentonite buffer to water channels in fracture zones in the rock. The KBS-3 system /6-4/ offers a greater variation of possible transport pathways up to the disturbed zone around the tunnel than other systems, but the transport pathway is deemed to be longer.

Nuclides that arrive at the disturbed zone around the blasted deposition tunnel in KBS-3 can, owing to its greater extent, more easily reach a subhorizontal zone with a short travel time to the biosphere than in MLH and VLH.

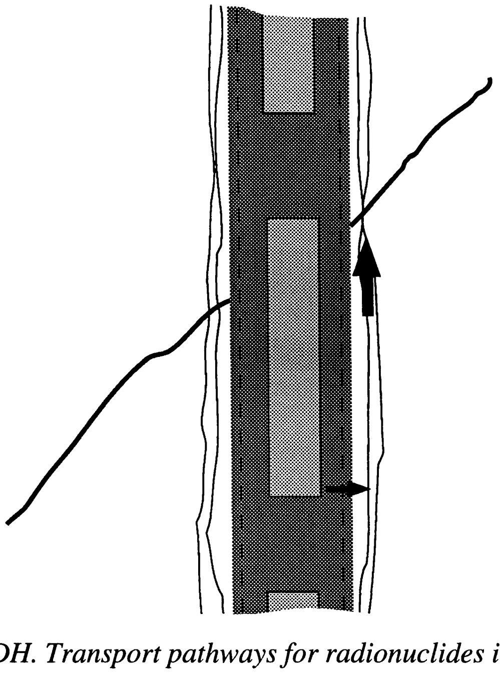


Figure 6-7. *VDH. Transport pathways for radionuclides in the near field.*

Water movements under the thermal pulse will have no importance for the systems at the 500 m level, since the life of the canisters covers the warmer part of this period. In the case of VDH, an effect can arise in the event the canisters are damaged early, which cannot be ruled out. However, a salt gradient in the groundwater towards greater depth has a potential for preventing upward transport, see the next section "*Far field*".

Far field

The far field includes the undisturbed rock mass through which the radionuclides must pass to reach the biosphere.

The rock's hydrological regime is of great importance for the travel time for radionuclides in the event the canister fails. The longer the travel times, the more time is available for nuclide decay.

Other rock properties with a positive effect are:

- suitable and stable chemical environment,
- stable mechanical environment,
- protection against events on the ground surface,
- protection against human intrusion.

Potential differences in release from the far field

Owing to its greater extent, A VLH repository is intersected by a larger number of fracture zones than a KBS-3 or MLH repository. If a large number of canisters are defective, radionuclides from a VLH repository will therefore emerge at many places in the biosphere. But the dose at each place will be lower than in the corresponding situation for a KBS-3 or MLH repository.

A VDH repository can be assumed to be intersected by a smaller number of fractures, due to the fact that the distance between fracture zones is expected to increase with increasing depth. The distance from broken canisters to a fracture zone must nevertheless be assumed to be short due to difficulties characterizing the bedrock at the depth in question.

The potential advantage of a repository at greater depth (VDH system), in comparison with the other repository systems (KBS-3, MLH and VLH) at smaller depths, is due to the following factors:

- longer transport pathway to the biosphere and thereby greater opportunities for retardation and decay of the nuclides in the rock,
- indications of lower hydraulic conductivity and smaller fractures at greater depths and associated lower water flows,
- increasing salinity with depth, with the associated positive effect of the salt gradient.

Investigations have been and are being conducted to verify rock conditions at great depths /6-7/. Salt analyses in the groundwater show increasing salinity with depth in crystalline bedrock both in the Gravberg hole and in holes in Russia and Ukraine, see Figure 6-8. Increasing salinity means increasing density of the water, which counteracts density reductions due to heating. If the salt gradient is known, it is possible to adjust the thermal load in the borehole so that the salt gradient always outweighs it. The effect of the salt gradient can, however, be difficult to confirm in view of the difficulty of determining salinity conditions at great depth and how stable conditions will be during the thermal pulse. The mathematical treatment has been demonstrated in /6-8 and 6-9/.

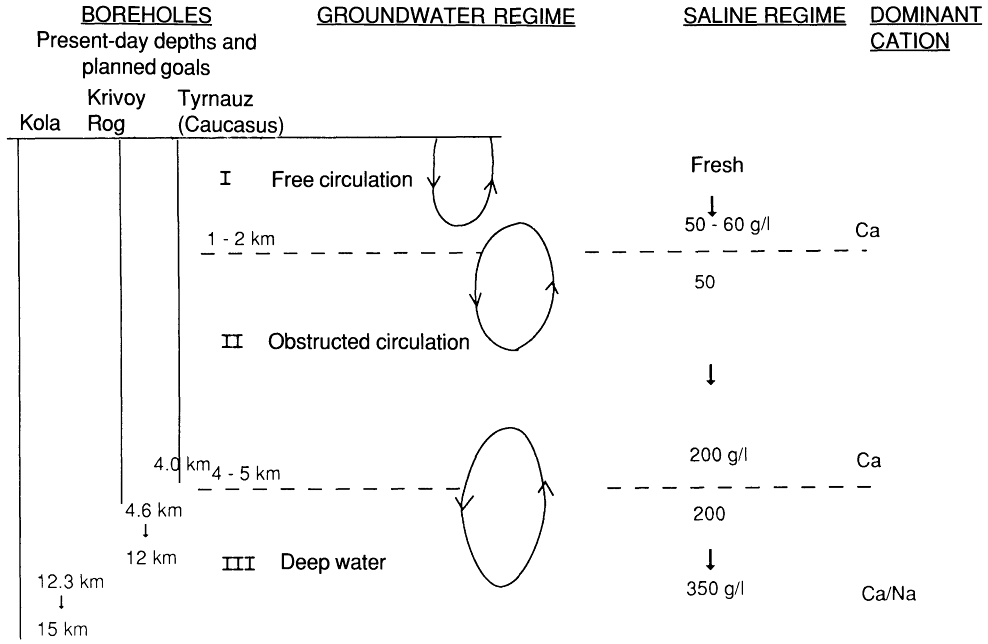


Figure 6-8. *Summary of bedrock conditions in the boreholes on the Kola Peninsula (Russia), in Krivoy Rog (Ukraine) and in Tyrnauz (Russia).*

Biosphere

The biosphere refers in this comparison solely to recipients in the form of soil, sediment and water. In other words, it has to do with the biosphere in a very simple form.

The biosphere dilutes released nuclides in superficial groundwater, lakes and rivers, and enriches nuclides in soil and sediment.

Potential difference in radionuclide transport in the biosphere

Radionuclides that reach the biosphere reach it via water pathways in the bedrock. The more water pathways there are, the more likely it is that the nuclides will be spread to more recipients. The maximum individual dose is hereby reduced, even though the collective dose remains the same. This effect is greater the more spread out the repository is and can be regarded as an advantage for VLH and VDH over KBS-3 and MLH in the event a large number of canisters are defective.

6.3.4 Comparison of repository systems

General

A quantitative measure of the performance and safety of a repository system is the dose to which man could conceivably be exposed in different assumed scenarios. The ambition in PASS has merely been to describe qualitatively the differences between studied systems that have been identified. Some uncertainty is therefore accepted in the result, especially when function is very similar and a qualitative analysis cannot distinguish two alternatives. The important thing has been to clarify whether large and important differences may exist.

A comparison between whole repository systems has been done for the following criteria:

- Radiological dose limits.
- Premises for validation.
- The multibarrier principle.
- Rare events and extreme events.

Radiological dose limits

KBS-3 is the reference system, since this system has been analyzed carefully in several safety assessments, most recently in SKB 91 /6-4/. In the normal case it takes a very long time before water can penetrate the canisters and get at the fuel to dissolve it. For the purpose of shedding light on the importance of the bedrock (which was the main purpose of SKB 91), it was assumed in a sample calculation that 5 deposited canisters were defective with holes through the copper shell. The lead fill prevented water entry for 1000 years. It was found that under these conditions the doses are insignificant.

A similar model has also been used in calculations for a VLH system with a copper/steel canister /6-10/. Under the assumption that 2 VLH canisters (1 canister per 1000) has an initial hole in the copper shell (2.5 mm in diameter), insignificant doses are obtained.

If similar calculations were to be carried out for MLH with a copper/steel canister, under the assumption that 5 canisters are broken from the start (holes in the copper shell), the result can be expected to be roughly the same as was obtained for the KBS-3 system, since the premises (canister size, repository geometry etc.) in the two cases are very similar.

Besides KBS-3, VLH and MLH are therefore also judged to be able to meet very stringent requirements with respect to long-term safety.

The VDH system has not been modelled and calculated through. A very large safety potential lies in the high and increasing salinity with depth indicated in several drillings. On the other hand, it has not been established as being the rule at depths of 2-4 km in the Swedish bedrock. The level of uncertainty for this system is accordingly greater than for the others, which means that further studies would be needed to enable a sufficiently accurate evaluation of safety to be done.

Premises for validation

Validation of engineered barriers appears to be able to be done with greater certainty than validation of natural barriers (the bedrock).

The KBS-3, MLH and VLH systems are very similar in this respect, while VDH deviates. The rock has an important function in this system, at the same time as certain properties of the barrier are judged to be difficult to determine with high accuracy today.

Multibarrier principle

The different barriers have different functions and effects for different nuclides /6-4/.

Canister life is very important for the isolation of relatively short-lived nuclides with high mobility. The distribution of canister failures (if any) in time is of importance for the dispersal of long-lived nuclides with high mobility in the bedrock.

The transport resistance of the bentonite buffer is of importance for short-lived nuclides if the canister has initial defects (or fails early), but is only of limited importance for long-lived nuclides.

The disturbed zone may be of importance for the dispersal of the nuclides from the near field to the far field. It can offer transport resistance, but also shortcuts.

The far field retards the transport to the biosphere. If the retardation is considerable the nuclides decay. Sorbing nuclides are retarded to an even greater degree.

For KBS-3, the performance of the different barriers has been assessed and found to meet the requirements of the "multibarrier principle". Comparison of the three other systems with KBS-3 shows that the performance of the barriers for MLH and VLH is very similar to that of the barriers in KBS-3.

For VDH, the canister and the bentonite buffer are of secondary importance for the performance of the entire system. The essential barrier is the bedrock with saline groundwater.

Common to all systems is the fuel's low solubility in groundwater. The long-lived nuclides that dominate the radiotoxicity after several hundred years have particularly low solubility.

Rare events and extreme events

Only "major rock displacements" and "human intrusion" are considered in the study.

The reason for rock displacement is assumed to be associated with a future glaciation. Rock movements are most likely to occur along major fracture zones. These will be avoided as locations for deposited canisters. VDH is more sensitive to minor displacements, but the effect is limited by the great distance between the deposition holes.

The risk of inadvertent human intrusion is equal for the three systems at 500 m depth, but much less for VDH. The risk of intentional intrusion is also judged to be less for VDH than for the other three systems.

6.3.5 Ranking - "Long-term performance and safety"

In summary, the analysis presented here of various differences between the long-term performance and safety of the different repository systems after the deep repository has been sealed shows the following:

The three systems with a deposition depth of about 500 m do not exhibit differences that warrant any distinction in ranking between the systems. They are therefore deemed to be equivalent with regard to long-term performance and safety.

The deep hole system VDH is deemed today to be more uncertain due to the fact that its long-term performance and safety are highly dependent on a single barrier (the bedrock) and the difficulty of assessing and validating the performance of this barrier. Improving the engineered barriers entails increased costs, see section 6.4.

6.4 COMPARISON AND RANKING WITH REGARD TO "COSTS"

6.4.1 General

The comparison of the systems has been done according to the model and the principles used in the annual calculation of the costs for all parts of the nuclear power waste management system. The lastest calculation is presented in PLAN 92 /6-11/

and is based on KBS-3 with lead-filled canisters. Based on the costs presented herein, the differences between KBS-3 and the other three systems have been estimated and costed. Adjustments have also been made in the KBS-3 calculation for the fact that the copper/steel canister replaces the copper/lead canister.

Quantities and costs are presented in /6-12/.

6.4.2 Premises in the calculations

In order to get as representative differences as possible between the compared systems, the data that affect the quantities of rock and backfill material have been chosen to be as similar as possible. There are examples of discrepancies, however. These, plus their effects, are commented on and discussed below.

Besides the data given in Appendices 1-4, the cost comparison is based on the following specific premises:

Number of canisters

The number of canisters used for each system in the cost comparison was calculated on the basis of the number of BWR assemblies. The PWR assemblies were converted to BWR equivalents, which were added to the number of BWR assemblies. The results are given in Table 6-4.

Canister choice

In accordance with section 6.1, a copper/steel canister is assumed in KBS-3, MLH and VLH, and a concrete-filled titanium canister in VDH. As a consequence of the fact that the encapsulation costs are roughly equal for VDH canisters with intact versus consolidated fuel assemblies, while the cost for the deep repository is changed considerably, the costs for both alternatives are reported.

Comments: The chosen alternatives are those that have been given priority in the canister ranking. With consolidation, it is assumed that twice as many rods fit in each canister.

Table 6-4. Number of canisters in cost comparison

From /6-11/ (operation of all plants through the year 2010):

Number of BWR assemblies	33 394
Number of PWR assemblies	3 858
Equivalent number of BWR assemblies:	
1 PWR assembly = $\underset{\text{kg U}}{\frac{470}{178}} * \underset{\text{burnup}}{\frac{41}{38}}$ = 2.85 BWR assemblies	10 995
TOTAL NUMBER OF BWR EQUIVALENTS	44 389

SYSTEM	NO. OF BWR ASSEMBLIES PER CANISTER	NO. OF OTHER CANISTERS CANISTERS	TOTAL FUEL	CANISTERS
KBS-3	12	3 699	46	3 745
MLH	12	3 699	46	3 745
VLH	24	1 850	23	1 873
VDH(non-cons.)	4	11 907	138	11 235
VDH(cons.)	8	5 548	69	5 617

Dimensions in the deposition position

The dimensions used are shown in Table 6-5.

Comments: The copper/steel canister in KBS-3 and MLH is 0.88 in diameter as per Figure B1-2a in Appendix 1. With a bentonite thickness of 0.35 m in both cases, the diameter of the deposition hole/drift is rounded off to 1.6 m (1.5 m in /6-11/). VLH has a bentonite thickness of 0.4 m. However, this thickness is on the small side to provide room for the deposition equipment, see Appendix 3.

Regarding the length of the canisters, the data in Table 6-5 pertain to encapsulation of assemblies without fuel boxes. The length of VDH has been taken from /6-13/, while Figure B4-2 in Appendix 4 shows the length with boxes.

The VLH canister is the version with flat ends, since other systems' canisters have flat ends. This choice does not affect the length of the deposition drifts, however, since the canister distance is independent of the shape of the ends. Costs for filling of the intervening spaces with bentonite blocks are included.

Table 6-5. Dimensions in the near field

SYSTEM	CANISTER DIAMETER m	CANISTER LENGTH m	BENTONITE THICKNESS m	HOLE DIAMETER m
KBS-3	0.88	4.58	0.35	1.6
MLH	0.88	4.58	0.35	1.6
VLH	1.6	4.99	0.4	2.4
VDH	0.5	4.4	0.15	0.8

Thermal premises

100°C is the maximum temperature permitted in the bentonite.

Comments: The VLH layout /6-14/ was designed for this temperature limit. In /6-11/, the limit is conservatively set at 80°C. In the comparison, the rock and bentonite quantities for both KBS-3 and MLH have been calculated for a limit of 100°C.

VDH cannot meet this temperature limit, due to the higher ambient temperature in the bedrock at great depth. The maximum temperature will be 120°C or 150°C, depending on whether four intact assemblies or eight consolidated ones are deposited in each canister.

The thermal conductivity of the bentonite is 1.5 W/m, K.

Comments: This value presumes water-saturated bentonite blocks, which the VLH layout is based on. The same premises have therefore also been used in the quantity calculations of MLH. The assumption militates against KBS-3, since for other reasons the deposition holes are not located as close to each other as the thermal conductivity of water-saturated bentonite would allow, see the discussion below.

Deposition geometry

The deposition geometries on which the quantity calculations are based are reported in Table 6-6.

Table 6-6. Geometries and total length of deposition tunnels (holes)

COLUMN	1	2	3	4	5	6
KBS-3	25	6.0	10	250 ^{4a}	25 100 ^{5a}	310 000
				7.6 ^{4b}	28 500 ^{5b}	60 000
MLH	25	5.0	10	250	22 000	340 000
VLH	100	5.9	22	4 500	13 500	60 000
VDH$_{\text{(non-consol.)}}$	500	5.4	25	2 000	76 000	160 000 ^{6b}
VDH$_{\text{(cons.)}}$	500	5.4	25	2 000	38 000	80 000 ^{6b}

LEGEND

Column 1: Distance between deposition tunnels (KBS-3, MLH and VLH) and deposition holes (VDH), respectively. (m)

Column 2: Centre-to-centre distance between canisters. (m)

Column 3: Allowance for unutilized canister positions. In VLH, an allowance of 450 m/deposition tunnel (totally 3 tunnels) is included for major discontinuities. (%)

Column 4: Nominal length per deposition tunnel (KBS-3^{4a}, MLH and VLH) and nominal depth in deposition hole (KBS-3^{4b} and VDH), respectively. (m)

Column 5: Total length of deposition tunnels (KBS-3^{5a}, MLH and VLH) and depth in deposition holes (KBS-3^{5b} and VDH), respectively. (m)

Column 6: Total quantity of mined rock in deposition tunnels and deposition holes (^{6a} includes tunnels in the deposition area, ^{6b} includes upper part of holes). (m)

Central area

Ramp from the ground surface plus a vertical shaft for personnel transports and vertical shafts for ventilation.

Comments: The VLH study proposed a ramp instead of shafts /6-14/. For the sake of the comparison, a ramp was chosen in all the systems located at a depth of about 500 m. The same size ramp and the same interior design have been assumed. The central areas have been designed accordingly. The size of the rock chambers is determined by the space required for excavation activities plus service etc. during the operating period.

Operating period

20 years in all alternatives.

Comments: The operating period affects e.g. the discounted present value and has been set equally long in all alternatives. This also means that the fuel's decay period is the same, which has been assumed in the calculation of the number of canisters, see Table 6-4.

6.4.3 Calculation results

Using the model in /6-11/, the costs have been calculated for

- common facilities (industrial area, harbour, railway, housing etc.),
- encapsulation plant,
- deep repository for spent nuclear fuel.

The deep repository sections for other long-lived wastes than fuel and for operational and decommissioning wastes are assumed to be the same for all studied systems. One possible difference is in the premises for the handling of the boxes, but this affects the costs only marginally.

For each facility the costs have been subdivided into:

- investment,
- operation,
- backfilling (bentonite/sand),
- decommissioning and sealing.

The results are shown in table 6-7, which shows the total cost and the total discounted present value. The latter was calculated as per January 1992 for a discount rate of 2.5%.

6.4.4 Discussion

The relative difference between KBS-3, MLH and VLH reported in Table 6-7 could possibly be altered as a consequence of: 1) uncertainties in the calculations that call for various contingency allowances, 2) discrepancies in the premises that militate against or in favour of different systems, and 3) potential development possibilities for the various systems.

Uncertainties in the calculations

The difference between KBS-3 and MLH is significant and is not affected by various uncertainties. Determinant factors are the quantity of rock to be excavated and the volume of sand/bentonite to be backfilled. These are less for MLH.

The result for VLH is affected by whether the canister costs for the VLH canister are overestimated. The cost difference is set to about 350% (the weight increase is also about 350%). A cost difference for the copper shell of about 235% is presented in /6-15/ provided that the VLH canister is made with flat ends and 400% if it is made with hemispherical ends. The fabrication cost for the steel canister was not studied. Since the total cost of canisters in the calculation is SEK 4 700 million for VLH and SEK 2 500 million for KBS-3, the total difference between VLH and KBS-3 (SEK 100 million) is substantially less than the uncertainty in the calculation.

Discrepancies in the premises

The canister choice in the calculation does not affect the ranking order between the systems. To be sure, a lead-filled canister is more expensive than the copper/steel canister, but if the copper/steel canister can be accepted in one system it should also be able to be accepted in the others at the same depth.

BWR assemblies without boxes are assumed in the canisters. This militates against VLH, which for the same cost would deposit assemblies with boxes and avoid the cost for parts of the separate repository for core components, which are estimated to cost about SEK 200 million.

Table 6-7. Summary of calculated costs – the total sum and the present value as per January 1992 for a discount rate of 2.5%

SYSTEM	COST MSEK	TOTAL SUM MSEK	COMP. FACTOR	PRESENT VALUE 2.5% MSEK	COMP. FACTOR
KBS-3					
- Common fac.	5 400				
- Encapsul.	6 800				
- Deep rep.	5 400	17 600	1.07	8 000	1.05
MLH					
- Common fac.	5 300				
- Encapsul.	6 800				
- Deep rep.	4 300	16 400	1.00	7 600	1.00
VLH					
- Common fac.	5 300				
- Encapsul.	8 800				
- Deep rep.	3 600	17 700	1.08	8 100	1.06
VDH non-cons.					
- Common fac.	5 300				
- Encapsul.	7 000				
- Deep rep.	32 100	44 400	2.71	19 600	2.58
VDH cons.					
- Common fac.	5 300				
- Encapsul.	7 100				
- Deep rep.	16 000	28 400	1.73	12 900	1.70

Conclusions:

1. The sum of the costs and the sum of their discounted values give the same relative difference between the systems.
2. VDH is considerably more expensive than other studied systems.
3. MLH is cheaper than KBS-3. The difference is significant, since the entire difference is attributable to the deep repository. The difference in common facilities is attributable to the handling of different quantities of bentonite and sand.
4. VLH is more expensive than KBS-3 and MLH. This is mainly due to the much more expensive canister for VLH (MSEK 2.5 canister as opposed to MSEK 0.7 canister for KBS-3).

The difference in bentonite thickness between KBS-3/MLH and VLH (0.35 m versus 0.4 m) means very little. A bentonite thickness of 0.35 m costs on the order of MSEK 50 less than a thickness of 0.4 m.

Bentonite's thermal conductivity

Reduced thermal conductivity in the bentonite affects VLH most and KBS-3 least. In the case of VLH, if the thermal conductivity is reduced from 1.5 W/m, K to 0.75 W/m, K, the maximum temperature of the canister surface increases by about 20% /6-14/. This can roughly be translated into having to reduce the thermal load in the canister by 20%, which requires more canisters, or alternatively having to make the canister so much larger than the cooling surface increases by 20%. More canisters and accordingly longer deposition tunnels entail a cost increase of about MSEK 1 100 (of which about MSEK 950 is for an increased number of canisters). An increase in canister size would probably be more expensive. (The diameter of the canister increases by 20% and the material quantities thereby increase by at least as much. Moreover, the tunnel area and the bentonite quantity around each canister increases.)

For MLH, the percentage change should be just as great as for VLH (has not been calculated, however). In this case the cost increase is around MSEK 600 (of which MSEK 500 for more canisters).

In KBS-3 the distance between the deposition holes can be retained even with the aforementioned lower thermal conductivity in the bentonite. This is due to the fact that the spacing of the holes already is considering a minimum distance that prevents direct hydraulic contact between the holes.

Potential development possibilities

From a cost viewpoint, both KBS-3 and MLH are judged to have great optimization potential. VLH can probably not achieve any appreciable cost saving.

In the layout, MLH has been designed with side tunnels (see Figure B2-1, Appendix 2), which are needed to enable the reamer head to be attached to the drilling rod during boring of the deposition tunnel. These side tunnels have, however, also been assumed to be so wide that deposition can be performed from them (7 m tunnel width). Otherwise less than half of the tunnel width would be sufficient. In addition, a considerable potential rationalization lies in the possibility of blind-hole-boring of the deposition tunnels. This would completely eliminate the side tunnels. Machine suppliers have displayed interest in the problem and say that it is solvable. The cost saving lies on the order of MSEK 500-600 if the side tunnels are eliminated entirely and MSEK 250-300 if the tunnel area is halved.

KBS-3 has two possibilities for savings. The smaller one numerically speaking consists of reducing the height of the deposition tunnels from 4.0 m, as assumed in the calculation, to about 3.7 m for the copper/steel canisters. Deposition equipment and drilling equipment for the holes able to do the work at the lower roof height are on the drawing board /6-13/. The cost saving is on the order of SEK 100 million. The other possibility is to drill some or all of the deposition holes deeper and make room in them for two canisters. The assessment is that this is possible, but the premises have not been analyzed in detail. In favourable cases, half the volume of deposition tunnels could be saved, which represents a cost of MSEK 700-800.

VLH already constitutes a simple layout in the assumed design. One point of discussion is, however, the investigation tunnel about 100 m below the repository level, which has been considered to be needed for investigation and final location of the deposition tunnels. The cost of the investigation tunnel is about MSEK 200.

6.4.5 Ranking - "Costs"

The following conclusions are reached on balanced consideration of both the basic calculation and the above discussion, see also Table 6-8:

1. VDH is the most expensive alternative.
2. MLH is the cheapest alternative.
3. KBS-3 and VLH have roughly the same costs. In the basic calculation, Table 6-7, the difference is small. The canister cost for VLH is important in this context. Another factor to be considered is that the costs under ground are lower for VLH, since that system requires less rock mining and less backfill material. A reduction of the thermal conductivity of the bentonite would, however, entail large cost increases for VLH. KBS-3 has a considerable rationalization potential if two canisters can be placed in every hole. Other discussed differences and development potentials do not provide additional criteria for selection between the systems. From a cost viewpoint, KBS-3 and VLH are therefore deemed to be equivalent in this study.
4. In the comparison between MLH and VLH, however, the difference in the basic calculation is greater. Moreover, it can be concluded that the material quantities in the canisters (copper and steel) are greater in VLH than in MLH. Furthermore, more bentonite is required around the VLH canisters than around MLH (provided that the canisters are located close to each other), while bored-out rock quantities are roughly the same. All of this presumes that 12 BWR assemblies can be packed into each MLH canister and 24 BWR assemblies in each VLH canister. The conclusion is that reasons exist for deeming VLH to be a more expensive alternative than MLH in a ranking.

Table 6-8. Ranking of studied systems with respect to the interim comparison "Costs". A ranking of 1 is the best.

SYSTEM	RANKING
KBS-3	2
MLH	1
VLH	2
VDH	4

7 CONCLUSIONS

7.1 RANKING OF CANISTER ALTERNATIVES

The interim comparison as well as the overall rankings are presented in chapter 5 "COMPARISON AND RANKING OF CANISTER ALTERNATIVES".

The rankings are:

KBS-3 and MLH	1. Copper/steel canister.
	2. Lead-filled copper canister.
VLH	1. Copper/steel canister (no ranking has been made between hemispherical or flat ends).
VDH	1. Concrete-filled titanium canister.

7.2 RANKING OF DEEP REPOSITORY SYSTEMS

The results from the interim comparisons of the four deep repository systems in chapter 6 for "Technology", "Long-term performance and safety" and "Costs" are summarized in Table 7-1. A weighing-together – under the provision that "Technology", "Long-term performance and safety" and "Costs" are given the same weight – leads to three groupings:

- KBS-3 and MLH,
- VLH,
- VDH.

Table 7-1. Summary of results from the three interim comparisons of repository systems. A ranking of 1 is the best.

DEEP REPOSITORY SYSTEM	TECHNOLOGY	LONG-TERM PERFORMANCE AND SAFETY	COSTS
KBS-3 (copper/steel canister)	1	1	2
MLH (copper/steel canister)	2	1	1
VLH (copper/steel canister)	3	1	2
VDH (concrete-filled Ti-canister)	4	4	4

VDH

Very Deep Holes, VDH, has been given the lowest ranking in all three interim comparisons. For both "Technology" and "Costs", the outcome was clear and indisputable. With regard to "Long-term performance and safety", the judgement is more open to discussion. The lower ranking is mainly due to the fact that the system's long-term isolating capacity is associated chiefly with only one barrier, the geosphere, on which present-day knowledge is limited at the relevant depths in Sweden.

An improvement of the engineered barriers ought to be possible, but at the price of higher costs. There is, however, no margin on the cost side. VDH is already the most expensive of the four systems in its analyzed form.

The higher costs of VDH and other disadvantages displayed by the system in comparison with the three other systems are significant. The study has not indicated any uncertainty in the analysis that might alter the situation in such a way that the VDH system is ranked first.

VLH

The main disadvantage with the Very Long Holes (VLH) system is the large canisters. These, in combination with small spaces next to the canisters in the tunnel, make the deposition technology less certain. It is more difficult to achieve the sought-after quality in the disposal operation.

Three premises chosen at the outset of the analysis which distinguish VLH from MLH are:

- over 4 km long deposition tunnels,
- large, heavy canisters,
- deposition technology with several remote-controlled machines with complex movement functions.

The long deposition tunnels are not system-specific, however. Attention was first focused on this concept in connection with the proposal to locate the deep repository below the seabed, where the hydraulic gradient is very small. With long tunnels you can get far out from land. A more compact layout was also sketched schematically in /7-1/. This principle was also checked with emplacement in exactly the same block at Finnsjön as that in which the KBS-3 repository was emplaced /7-2/. It was found that a VLH repository is also accommodated within the block. The difference between VLH and MLH can thus be minimized.

The larger canister is, on the other hand, specific for the system.

The deposition technology also distinguishes VLH and MLH. The dimensions in the MLH tunnel are so much smaller than in the VLH tunnel (1.6 m in diameter as compared to 2.4 m) that the VLH technology /7-3/ is not judged to be applicable in MLH. Mechanically less complicated but slower equipment was chosen for MLH than for VLH /7-4/. Both methods exhibit both advantages and disadvantages in a comparison. A general assessment is that the deposition technology proposed for VLH is preferable. With a more compact layout, the differences between these alternatives are thus lessened.

With regard to the cost comparison the outcome is more distinct, even though the difference in absolute terms may appear to be relatively small. For VLH it is the canister cost that is decisive. With the values reported in this study, the larger VLH canister is uneconomical compared with the canister of KBS-3 size.

On top of this, KBS-3 and MLH offer more options when it comes to canister design. Only for these systems does metal filling appear to be a realistic alternative.

KBS-3 and MLH

The choice between these two systems must be based on an evaluation of "Technology" against "Costs". "Long-term performance and safety" has been demonstrated by both qualitative and quantitative analyses to be equivalent for the two systems, see section 6.3.

For "Technology" it is above all the deposition procedure that tips the balance in the ranking in section 6.2 /7-5/. In MLH, the emplacement of the bentonite buffer is based on remote-controlled technology with small spaces between the equipment and the rock wall. Canister emplacement takes place horizontally in the middle of the bentonite buffer by insertion of the canister into the prepared hole. The deposition procedure has to take place in one uninterrupted sequence in each tunnel, in view of the fact that the bentonite begins to swell when it comes into contact with water. In KBS-3 the bentonite blocks can be emplaced using simpler technology (even manually). The canister is emplaced in the hole by being lowered down, which facilitates vertical adjustments. The deposition of each canister is a closed, self-contained operation, which offers flexibility with regard to interruptions and planned pauses.

The overall assessment is that the technical advantages of KBS-3 have a greater value than the economic advantages of MLH. KBS-3 is therefore ranked ahead of MLH.

7.3 RESULTS OF PASS

The conclusions of the study are:

1. Canisters with room for 12 BWR assemblies, or an equivalent thermal load, (KBS-3) are recommended over canisters with twice the load (VLH).
2. A copper-clad steel canister (composite canister) is recommended. The previous reference canister – lead-filled copper canister – is ranked second and ahead of other studied alternatives.
3. The KBS-3 system is recommended.

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KBS-3 SYSTEM

The appendix has been prepared for the purposes given in the body of the report.

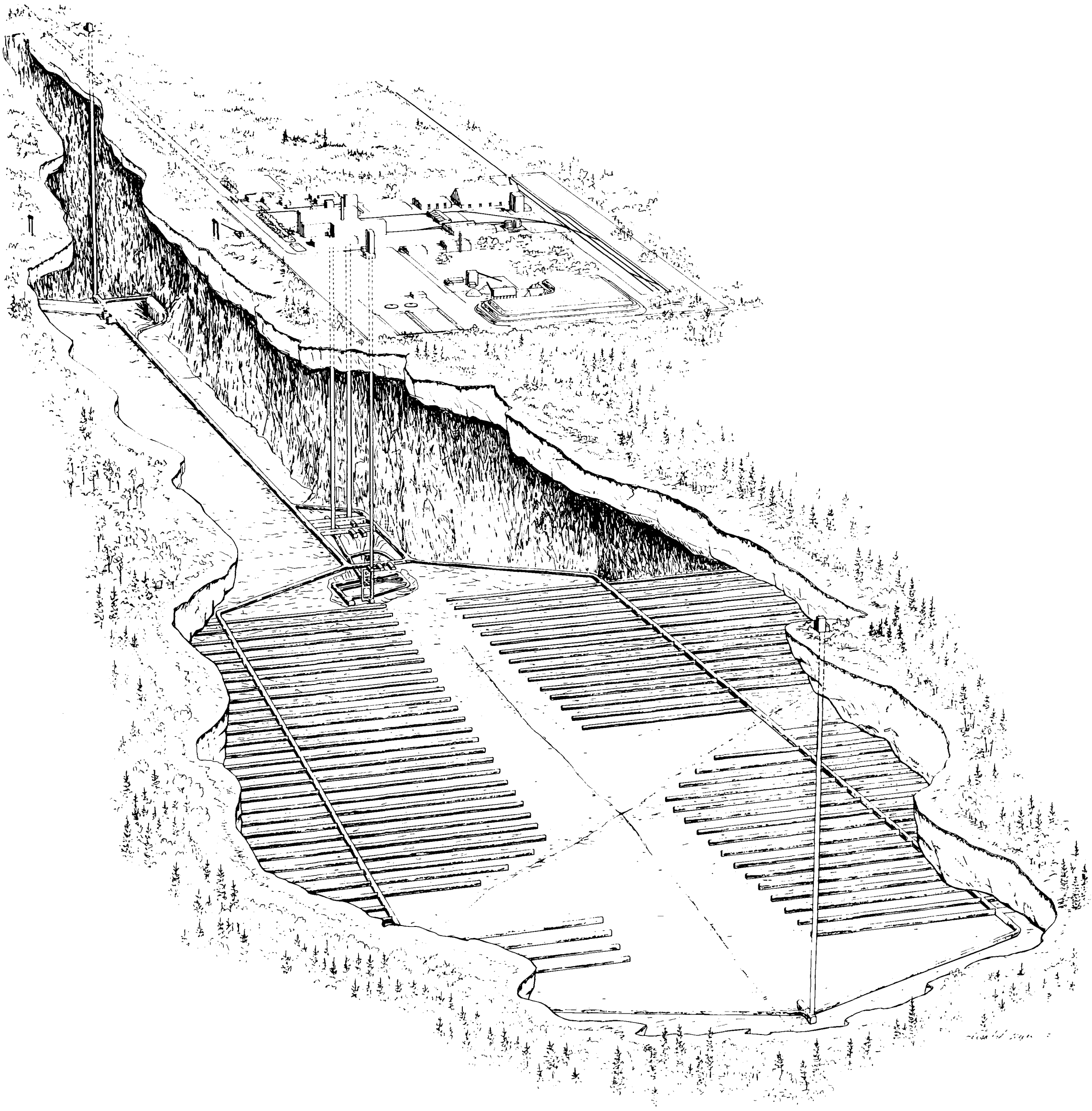


Figure B1-1. *Plan of the facilities.*

1 CANISTER ALTERNATIVES

The canister alternatives that have been analyzed are:

A. Steel canister with copper shell (composite canister), see Figure B1-2a and b. TVO's ACP (Advanced Cold Process) canister is based on the same principle but has a slightly smaller diameter in its basic version: 822 mm or 802 mm. The internal free volume can be filled out with particulate material in the cold state.

B. Copper canister filled with lead, see Figure B1-3a and b. Lead filling takes place by pouring molten lead into a hot canister containing fuel assemblies. The whole canister is then allowed to cool in a carefully controlled manner. This design comprises the reference design in the annual cost calculations, the most recent being PLAN 92 /B1-1/.

C. Copper canister fabricated by HIP (Hot Isostatic Pressing), see Figure B1-4a and b. This alternative comprised one of the two alternatives presented in the KBS-3 report in 1983 /B1-2/.

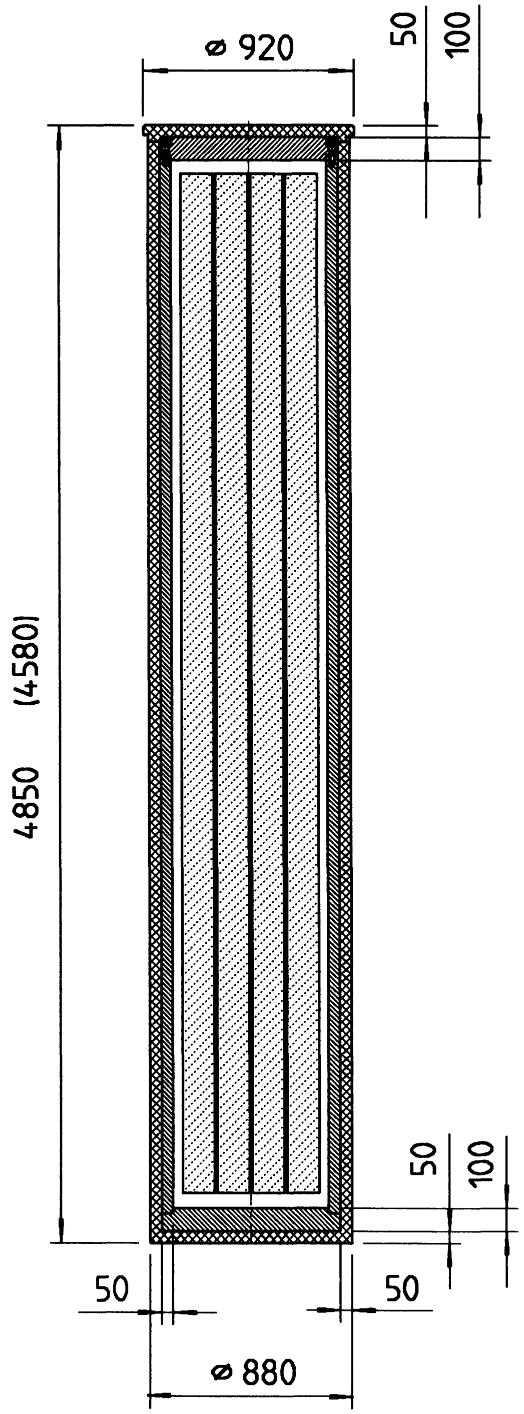
D. Steel canister filled with lead, see Figure B1-5 (only drawn for BWR elements). In PASS this alternative is called "Gripsholm".

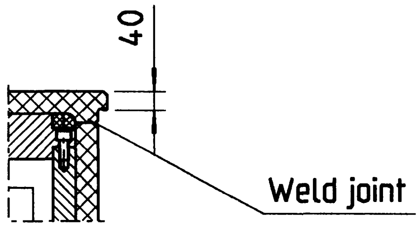
E. Steel canister, see Figure B1-6. The inner, free volume has been filled out with particulate material in the cold state.

2 COMMON FACILITIES

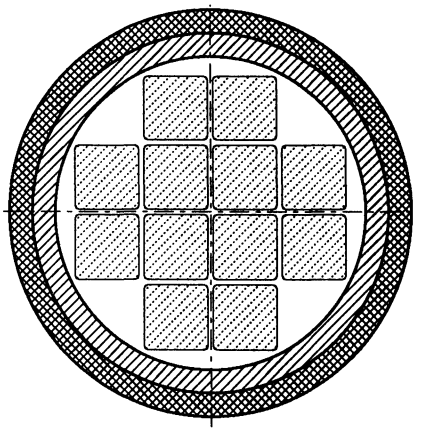
The prerequisite for the cost calculation is that the encapsulation plant and the deep repository for final disposal are sited at the same geographic location. This is assumed to be situated so as to permit both sea and rail transport of the spent nuclear fuel. This arrangement is taken from /B1-1/, which differs from the proposal with encapsulation plant at CLAB presented in FUD-Programme 92. With co-siting of the encapsulation plant and the deep repository, a number of supply and service systems can be assumed to be common. This applies in particular to the transportation system and the plant area. From the viewpoint of technology and performance, there is nothing to distinguish the different repository systems (KBS-3, MLH, VLH and VDH) when co-siting is assumed until the fuel, after transport, has been handled and encapsulated. The following description is based on a co-siting somewhere in the interior of Sweden.

It is assumed that the fuel is collected at CLAB and transported by ship to the nearest harbour that can be considered suitable for this type of transport after certain improvements of the navigation channel and the quay facilities. From there the fuel is transported by rail to the industrial area on the site.





Detail of lid lip

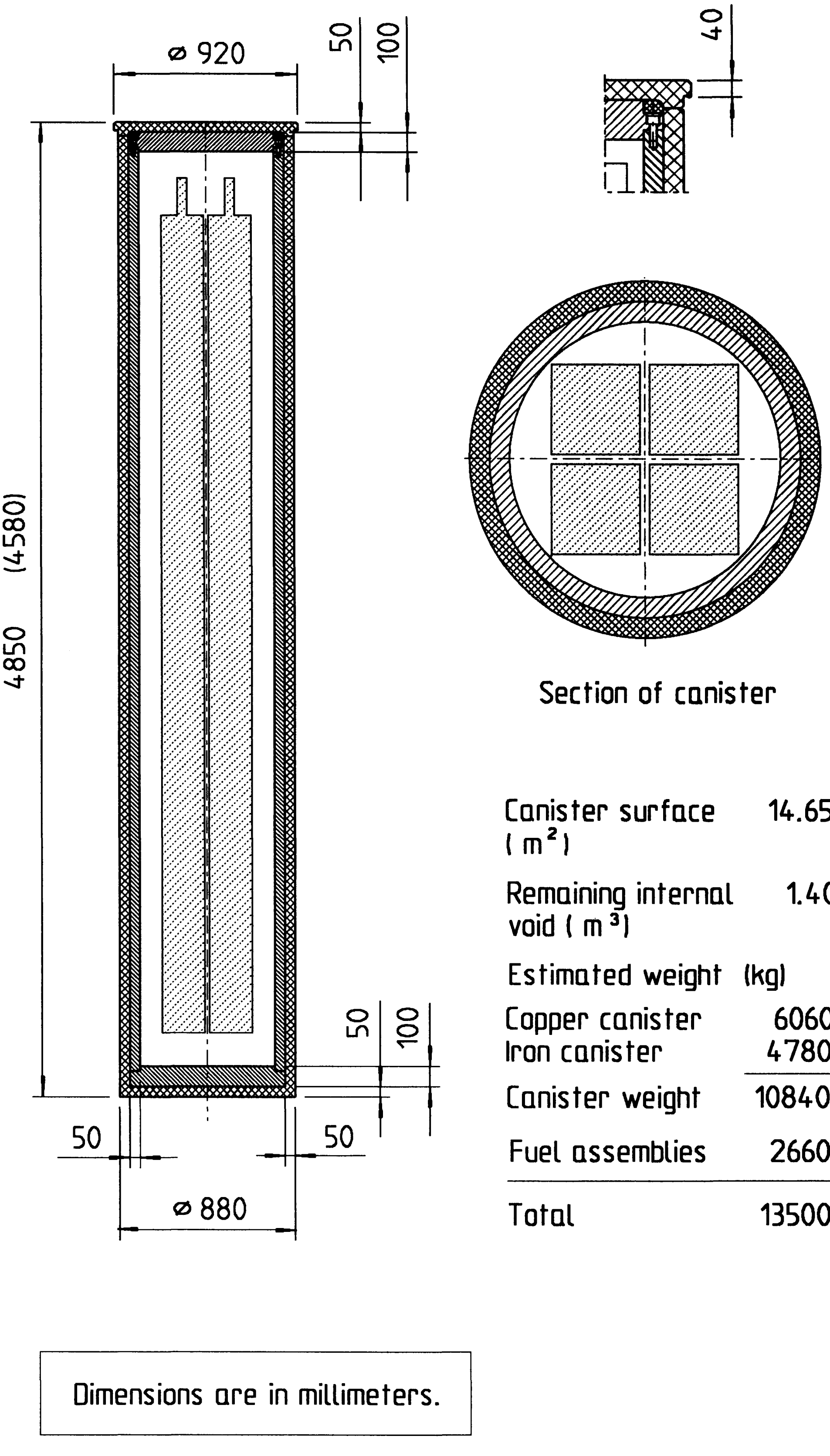


Section of canister

Canister surface (m^2)	14.65	(13.90)
Remaining internal void (m^3)	1.22	(1.17)
Estimated weight (kg)		
Copper canister	6060	(5750)
Iron canister	4780	(4540)
Canister weight	10840	(10290)
Fuel assemblies	3640	(3240)
Total	14480	(13530)

Dimensions and weights within brackets apply to canister containing BWR assemblies without boxes.
Dimensions are in millimeters.

Figure B1-2a. *Copper/steel canister with BWR assemblies.*

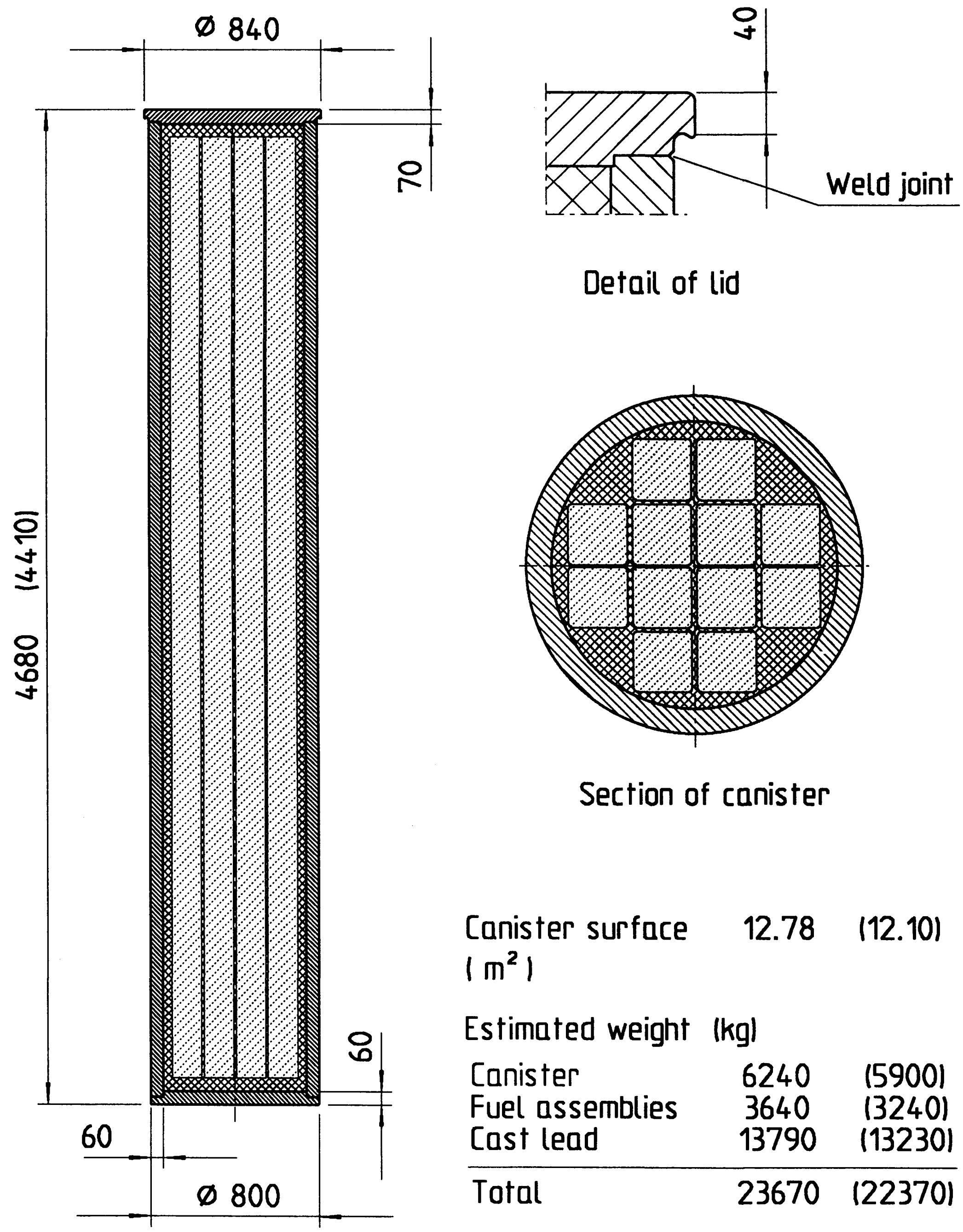


Section of canister

Canister surface (m^2)	14.65
Remaining internal void (m^3)	1.40
Estimated weight (kg)	
Copper canister	6060
Iron canister	4780
Canister weight	10840
Fuel assemblies	2660
Total	13500

Dimensions are in millimeters.

Figure B1-2b. *Copper/steel canister with PWR assemblies.*



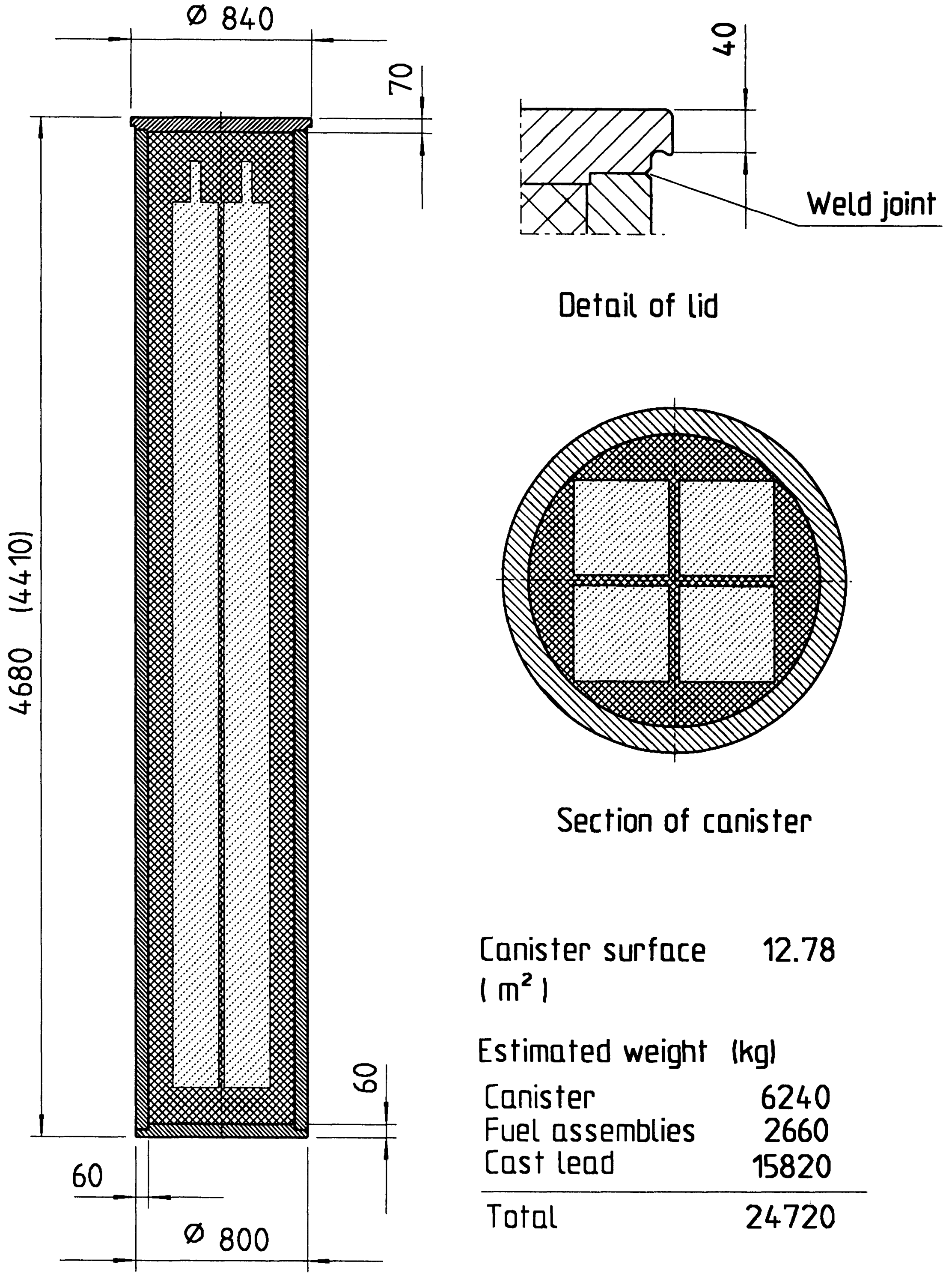
Detail of lid

Section of canister

Canister surface (m^2)	12.78	(12.10)
Estimated weight (kg)		
Canister	6240	(5900)
Fuel assemblies	3640	(3240)
Cast lead	13790	(13230)
Total	23670	(22370)

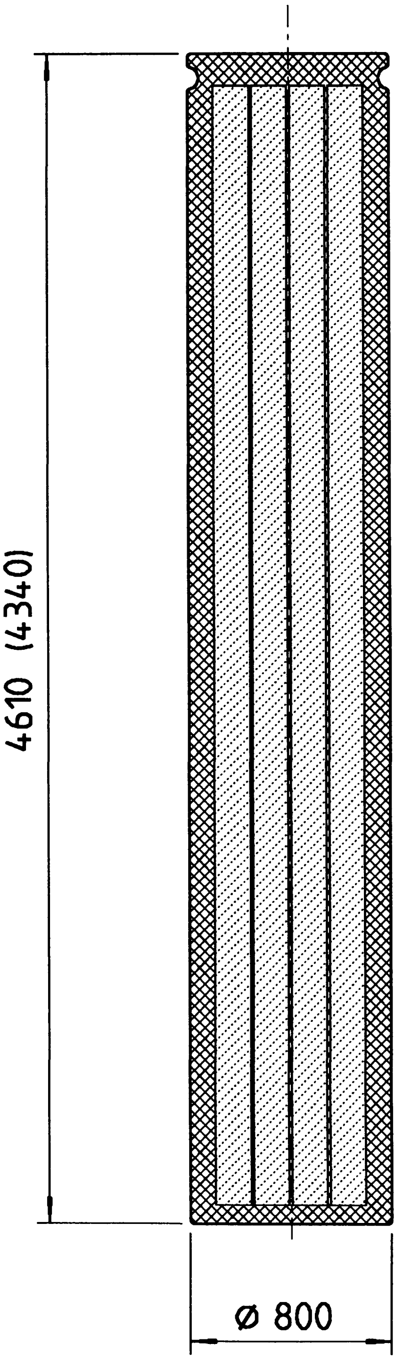
Dimensions and weights within brackets apply to canister containing BWR assemblies without boxes.
Dimensions are in millimeters.

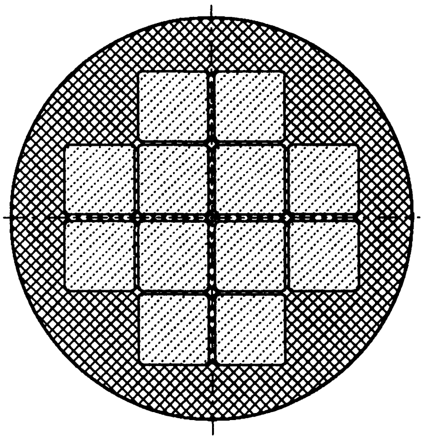
Figure B1-3a. *Copper/lead canister with BWR assemblies.*



Canister surface (m^2)	12.78
Estimated weight (kg)	
Canister	6240
Fuel assemblies	2660
Cast lead	15820
Total	24720

Figure B1-3b. *Copper/lead canister with PWR assemblies.*



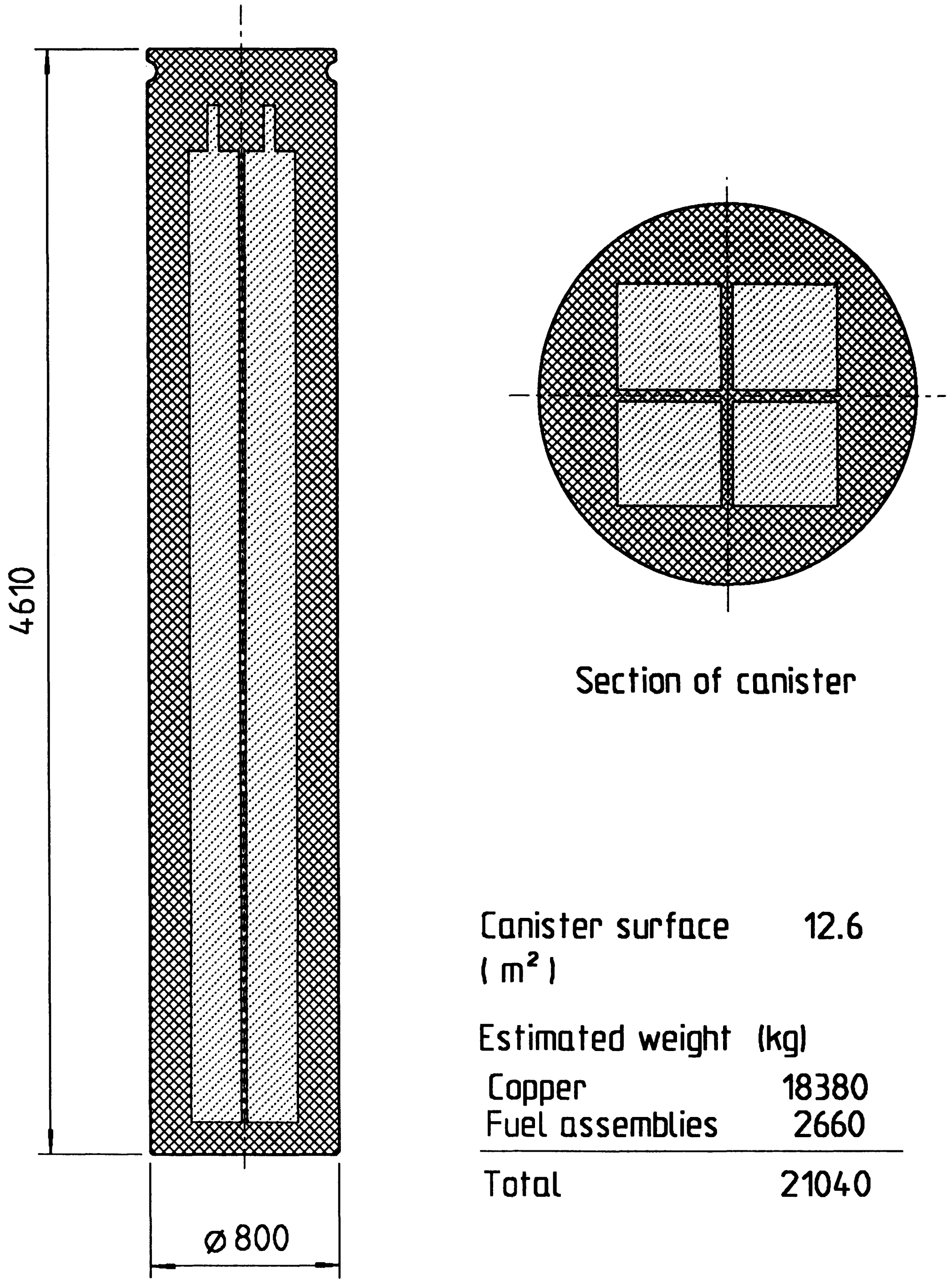


Section of canister

Canister surface (m^2)	12.6	(11.9)
Estimated weight (kg)		
Copper	16780	(16000)
Fuel assemblies	3640	(3240)
Total	20420	(19240)

Dimensions and weights within brackets apply to canister containing BWR assemblies without boxes.
Dimensions are in millimeters.

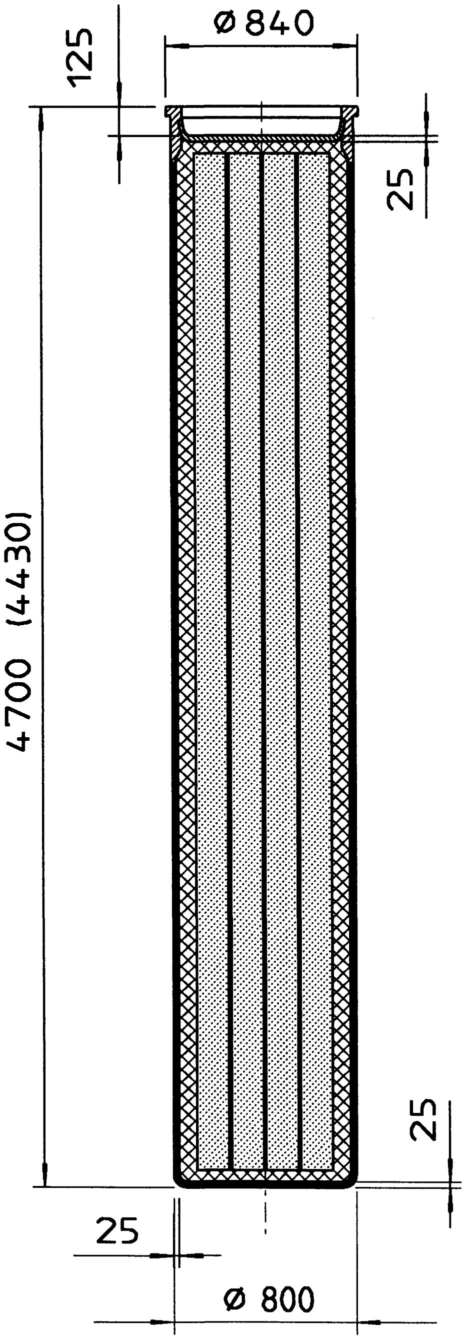
Figure B1-4a. *Copper canister – HIP – with BWR assemblies.*



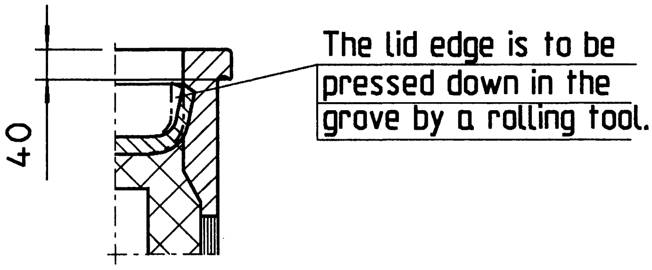
Canister surface (m^2)	12.6
Estimated weight (kg)	
Copper	18380
Fuel assemblies	2660
Total	21040

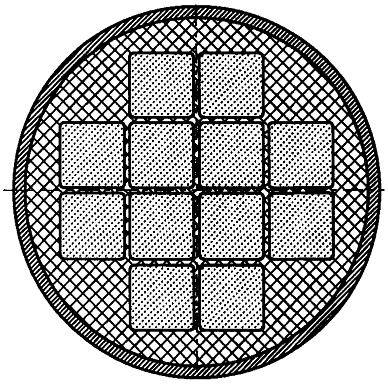
Dimensions are in millimeters.

Figure B1-4b. *Copper canister – HIP – with PWR assemblies.*



Detail of lid



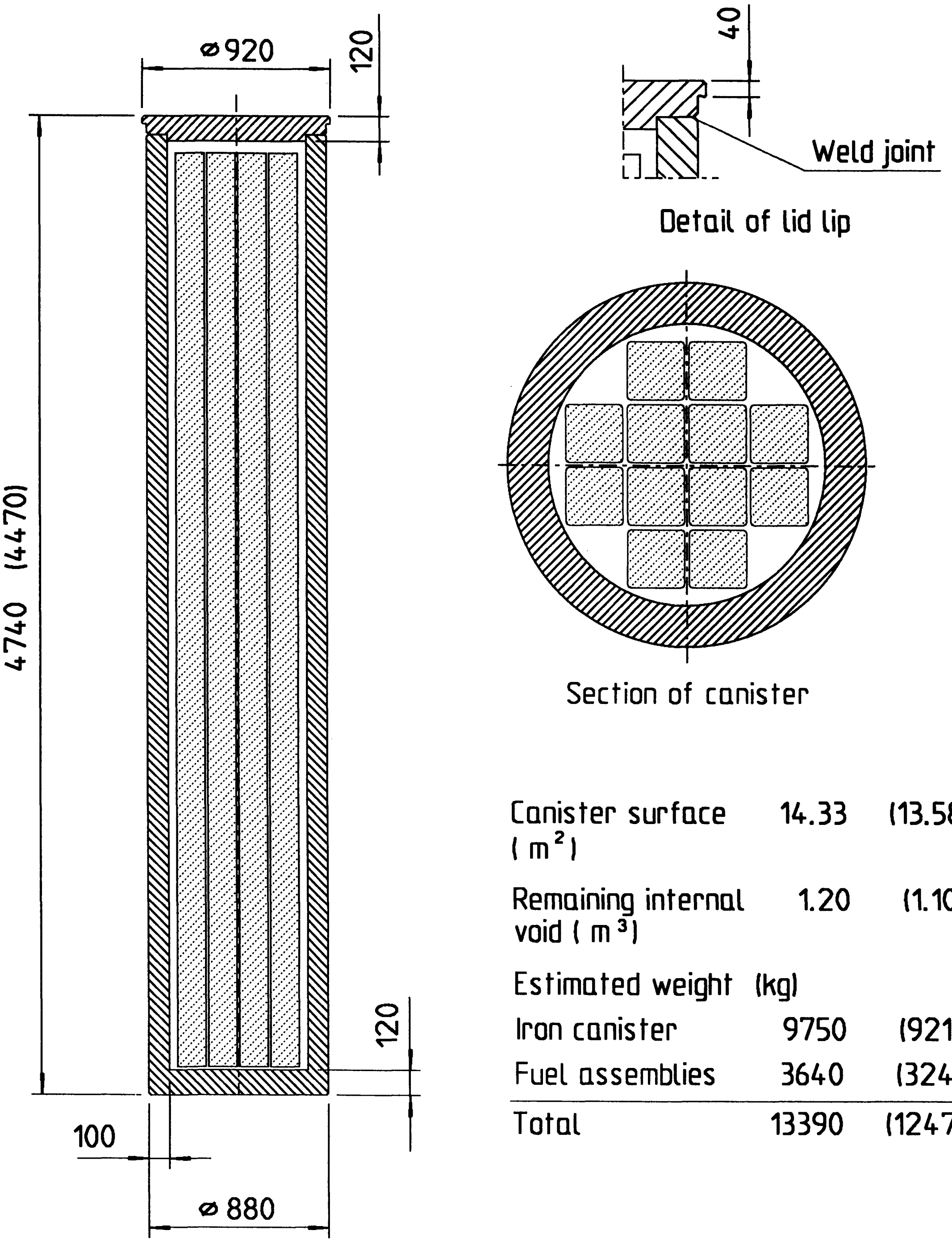


Section of canister

Canister surface (m^2)	13.98	(12.30)
Estimated weight (kg)		
Canister	2500	(2370)
Cast lead	17700	(16360)
Fuel assemblies	3640	(3240)
Total	23840	(21970)

Dimensions and weights within brackets apply to canister containing BWR assemblies without boxes.
Dimensions are in millimeters.

Figure B1-5. *Steel/lead canister with BWR assemblies (Gripsholm).*



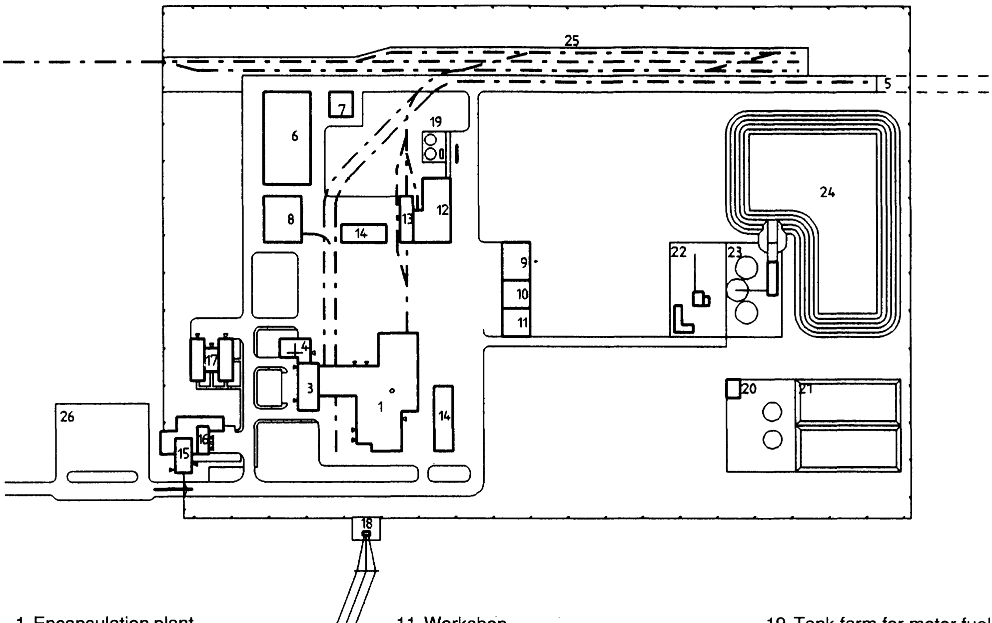
Detail of lid lip

Section of canister

Canister surface (m^2)	14.33	(13.58)
Remaining internal void (m^3)	1.20	(1.10)
Estimated weight (kg)		
Iron canister	9750	(9210)
Fuel assemblies	3640	(3240)
Total	13390	(12470)

Dimensions and weights within brackets apply to canister containing BWR assemblies without boxes.
Dimensions are in millimeters.

Figure B1-6. *Steel canister with BWR assemblies.*



1 Encapsulation plant
3 Administration building
4 Elevator building for personnel shaft
5 Ramp to deep repository
6 Sand storeroom and mixing station
7 Silos for bentonite
8 Factory for fabrication of bentonite blocks
9 Heating plant
10 Water treatment with firewater reservoir and pumps
11 Workshop
12 Vehicle workshop
13 Wagon hall for defrosting and washing
14 Cold store
15 Entrance and information building
16 Fire station
17 Canteens and occupational health services
18 Switchgear 220/10 kV
19 Tank farm for motor fuels and fuel oil
21 Settling ponds
22 Concrete plant
23 Crusher and sorting plant
24 Rock pile
25 Shunting yard
26 Parking

Figure B1-7. *Layout of common facilities.*

The layout of the plant area is shown by Figure B1-7. Aside from the encapsulation plant, which is the dominant building, the area will contain the following facilities:

- entrance building
- fire station
- workshops
- goods reception station
- vehicle service
- concrete station with crusher
- storage buildings for backfill material and handling of bentonite
- plant for pressing of bentonite blocks
- rock pile for muck from underground work
- personnel quarters
- canteens
- offices
- facilities for water supply and sewage treatment, electricity supply etc.

Several of these facilities affect the comparison of "Costs", since the four different studied systems handle different quantities of material. The greatest deviation from the above description is, however, exhibited by VDH, see Appendix 4.

3 ENCAPSULATION PLANT

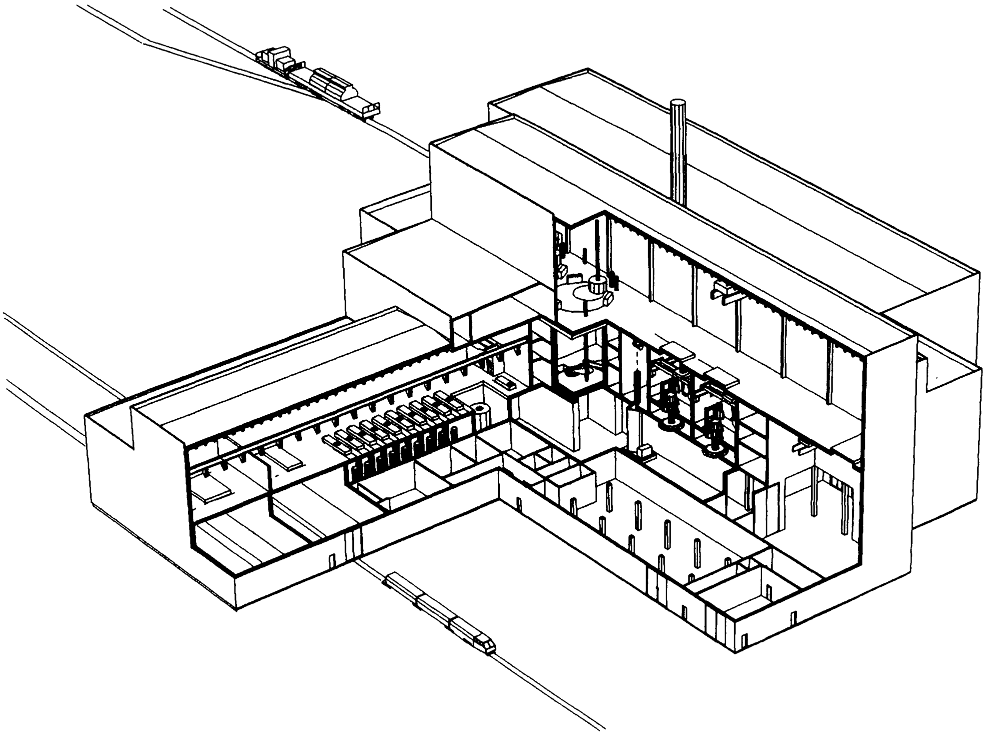


Figure B1-8. *Encapsulation plant for copper/steel canisters.*

A drawing of the encapsulation plant is shown in Figure B1-8. The building contains the functions that are required for reception, handling and encapsulation of the spent nuclear fuel in canisters of type A above, i.e. composite canisters. The additions that are required for lead casting are described below. A lead-filled steel canister and a steel canister of type D make no extra demands on additional functions beyond those required for the equivalent copper alternatives. The HIP canister's special systems are described in /B1-3/.

The encapsulation plant is designed for an encapsulation rate of one canister/day, for all the canister alternatives.

The encapsulation plant shown in the drawing in Figure B1-8 also contains a receiving station for core components and reactor internals, which are embedded in concrete moulds in a special part of the station. The canister designs in Figures B1-2a, B1-3a and B1-4a show the dimensions for BWR assemblies with and without boxes. In PASS, however, the alternative without boxes has been assumed, since the costs in /B1-1/ were calculated for this alternative. (This choice militates against VLH slightly from the cost viewpoint, see discussion in section 6.4.4 in the main text.) The fuel boxes, which are transported together with the fuel, make up a large portion of the core components. In addition, the encapsulation plant contains a receiving section for operational waste from CLAB and long-lived waste from Studsvik. The units that exist for other waste besides spent nuclear fuel are of no relevance to the comparison of the four repository systems, but are described here because the costs for the units have been included in the cost section, see section 6.4, which is based on the total cost in /B1-1/.

The encapsulation plant is divided into the following functional parts:

- Arrival and receiving section.
- Encapsulation and despatch section for fuel.
- Encapsulation section for core components (concrete casting)
- Service section, located alongside the encapsulation section and containing stores.
- Auxiliary systems with cooling and ventilation systems as well as electrical and control equipment.
- Side building with personnel quarters and offices.

The location of the functions in the station is shown by Figure B1-9. Encapsulation of the fuel takes place in areas 1-5. Buffer storage of filled canisters takes place in area 8 and placement of canisters in transport casks for further transport down under ground is done in area 9. (Embedding of core components and reactor internals in concrete is done in areas 6 and 7. Buffer storage of moulds takes place in area 8 and loading into transport casks for transport down under ground takes place in area 9. Operational waste from CLAB is received in area 10, where it is also transferred to radiation-shielded containers for transport down under ground.)

Handling of spent fuel is illustrated by the flow scheme in Figure B1-10. The following stations are distinguished:

- Reception of transport casks.
- A railway wagon with transport cask is driven into the encapsulation plant's arrival hall, where it is examined. From there it is taken into the encapsulation plant and kept in a buffer store until it is time to unload the fuel (or core components) from the cask.

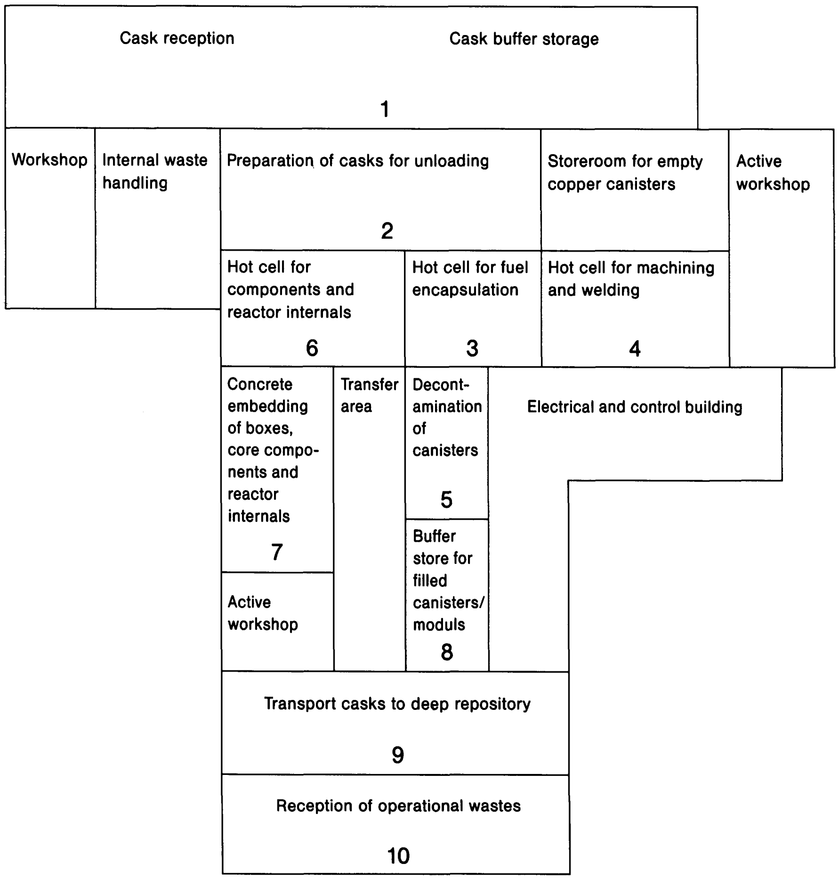


Figure B1-9. *Schematic layout of encapsulation plant*

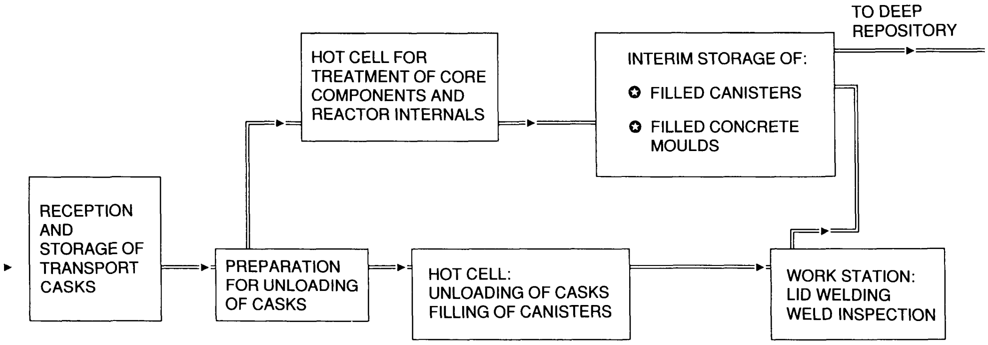


Figure B1-10. *Flow scheme for handling of spent fuel in encapsulation plant.*

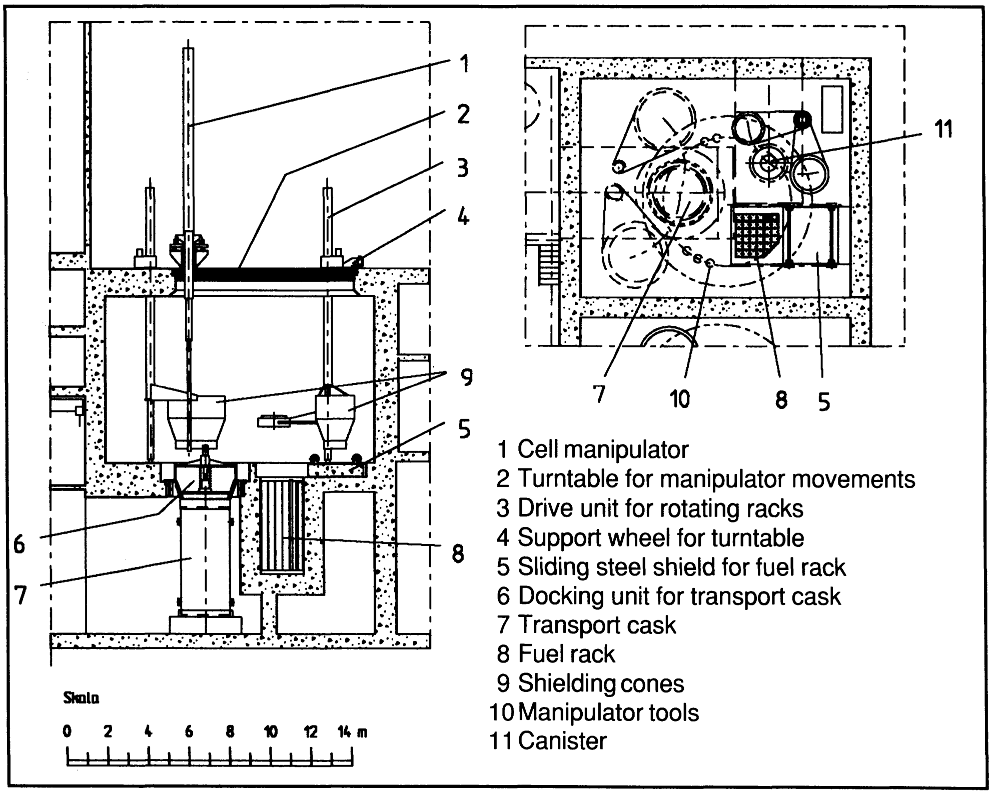
- Preparations for unloading of cask.
  In a separate work position the outer lid is removed and the cask is connected to the hot cell for removal of fuel (or of core components).
- Hot cell.
  The design of the hot cell for spent nuclear fuel is shown in Figure B1-11. The cask's contents of fuel assemblies are transferred to a fuel rack in the hot cell or directly to the canister. The BWR assemblies are thereby lifted out of their boxes, which remain in the transport cask. After concluded unloading, the cask is taken away and moved to the cell for core components for removal of the BWR boxes. The steel canister has been fitted in the copper shell and the entire unit has been enclosed in a radiation shield. The canister is then filled with the particulate material, the steel canister's lid is put on and the canister is transferred to the welding station.
- Machining and welding.
  Welding of the canister lid is done by means of electron beam welding in a fully automatic process. After welding, the weld is checked by ultrasonic inspection. If the weld is approved, the canister is transferred to despatch inspection. If the weld cannot be approved, it is cut open and a new lid is welded on. The old lid is discarded after cleaning.
- Core components and reactor internals.
  The transport cask with boxes or the special transport cask with reactor internals from CLAB is docked to a special hot cell. There the contents of the cask are lifted over to a concrete mould. When the mould is full, a lid is placed on it and it is filled with concrete by injection.

Copper canister filled with cast lead

This encapsulation process requires an extra station where heating and cooling constitute the principal operations. The station looks the same as for the lead-filled steel canister alternative.

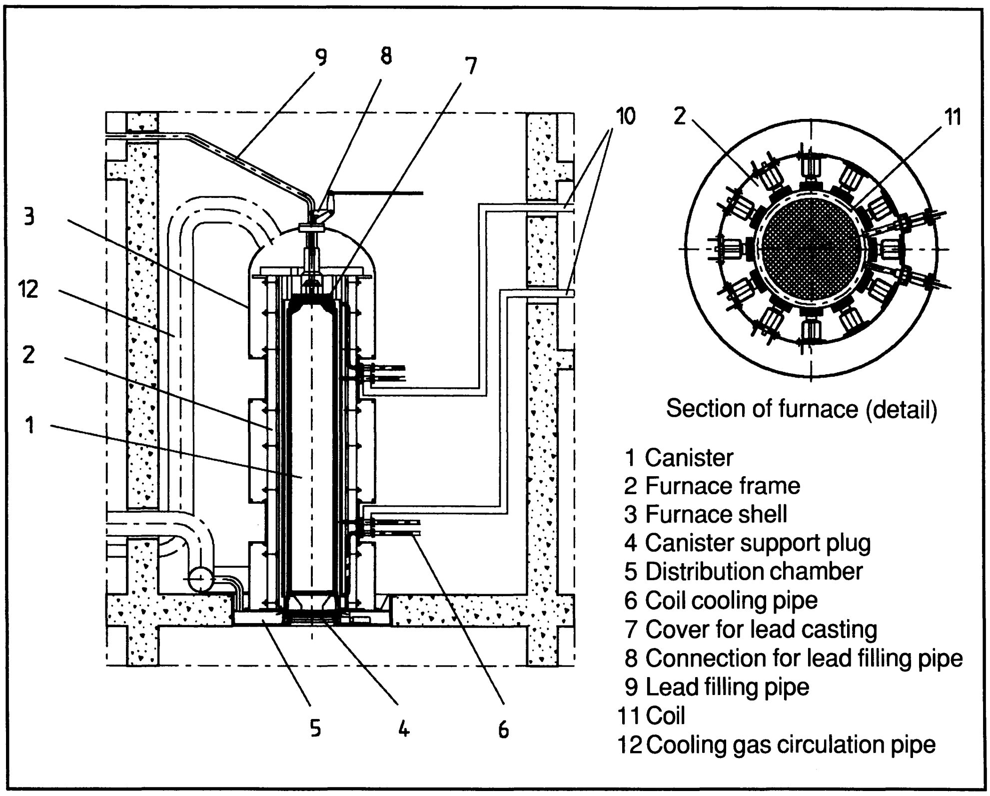
- Induction furnace.
  The design of an induction furnace is shown in Figure B1-12. From the hot cell, the canister is moved to a furnace position and the canister is brought up into the furnace, which is closed.
  The furnace heats the canister with fuel to about 380°C in about 6 hours. Molten lead is then added and allowed to solidify slowly. Solidification is controlled so that it takes place from the bottom upwards so that no cavities are created. Cooling from the lead's solidification temperature, 327°C, to about 60°C can take place in 12 hours. The entire operation in the induction furnace is timed to take 24 hours per canister.

From the induction furnace, the canister is transported to the welding cell, which, compared to the cell for the copper/steel canister, also contains units for machining of the top surface of the lead before the canister lid is put on.



1 Cell manipulator
2 Turntable for manipulator movements
3 Drive unit for rotating racks
4 Support wheel for turntable
5 Sliding steel shield for fuel rack
6 Docking unit for transport cask
7 Transport cask
8 Fuel rack
9 Shielding cones
10 Manipulator tools
11 Canister

Figure B1-11. *Hot cell.*



Section of furnace (detail)

1 Canister
2 Furnace frame
3 Furnace shell
4 Canister support plug
5 Distribution chamber
6 Coil cooling pipe
7 Cover for lead casting
8 Connection for lead filling pipe
9 Lead filling pipe
11 Coil
12 Cooling gas circulation pipe

Figure B1-12. *Canister placed inside induction furnace for lead filling.*

4 DEEP REPOSITORY FOR SPENT NUCLEAR FUEL

4.1 DESIGN

The deep repository for the encapsulated fuel is assumed to be situated at a depth of 500 m below the surface. It can be reached from the surface via a ramp (canisters and materials) and an elevator shaft (personnel). In /B1-1/, the layout is based on communication and transport in shafts alone. In the present study, the repository systems are designed as similarly as possible in those parts that are not system-specific. A ramp is chosen for communication systems, as recommended in the analysis of the VLH system.

The facility at 500 m consists of a system of parallel deposition tunnels with associated transport tunnels, service area and ventilation system, see the general plan in Figure B1-1. In practice the layout will be determined by the local conditions in the selected rock volume. The size of the facility is determined above all by the heat generation in the deposited fuel. The costs have been calculated for the layout shown by Figure B1-13.

The waste canisters are deposited in vertical holes drilled in the floors of the deposition tunnels. Design and dimensions are shown in Figure B1-14 (copper/steel canister as per Figure B1-2a).

The repository consists of a central section, containing service areas, plus a deposition section. The central section is connected with the surface via a ramp and a shaft:

The ramp constitutes the main communication pathway between the surface and the deep repository. The ramp contains both a track for a train and a roadway for haulers and other vehicles. Rock is hauled up and canisters and backfill materials etc. are transported down via a ramp.

The service shaft is equipped with an elevator for personnel transport and with utility lines for supply of air, water, electricity etc. to the repository. Another shaft is located at the opposite end of the tunnel system. This shaft normally serves as an exhaust air shaft, but in an emergency situation it can also be used for personnel evacuation.

The repository is divided into two parts during the deposition period to permit a simple physical separation of the deposition work from other activities such as excavation and backfilling. Excavation of the deposition tunnels is planned to be done as the deposition work proceeds.

4.2 EXCAVATION TECHNOLOGY

It is assumed that the access ramp will be driven by means of the TBM (Tunnel Boring Machine) method. A model in Sweden is the Klippen tunnel (hydropower project), the first 100 m of which was driven at a downward gradient of 1:10, after which it levelled out to horizontal boring. In the case with the deep repository for spent nuclear fuel, a gradient of 1:7 is assumed. The excavated rock is hauled out by the type of train with buffer storage bins that is used in Klippen. The RHS (Rapid Haulage System) train is illustrated in Figure B1-15.

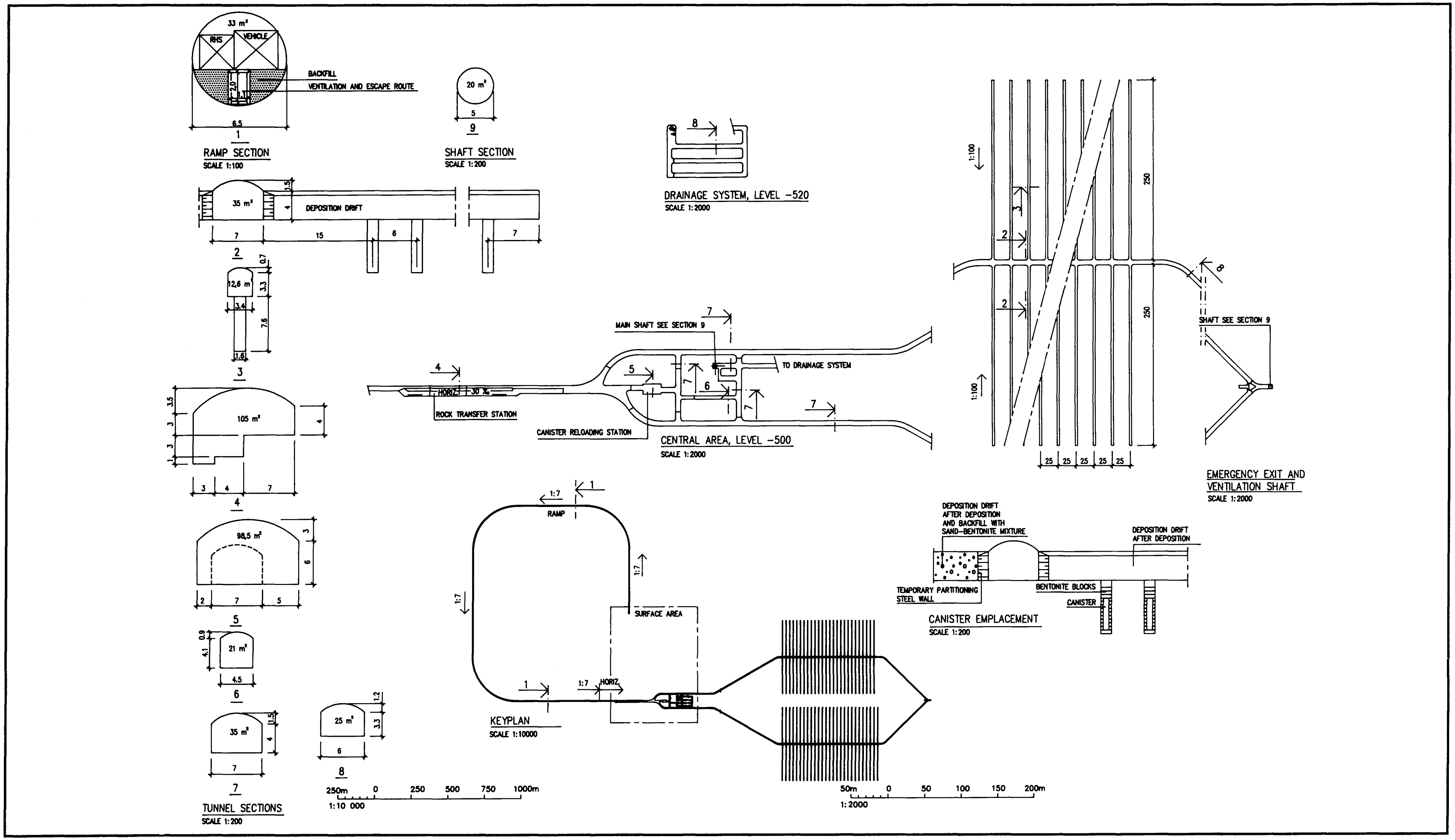


Figure B1-13. Base for cost calculations – KBS-3.

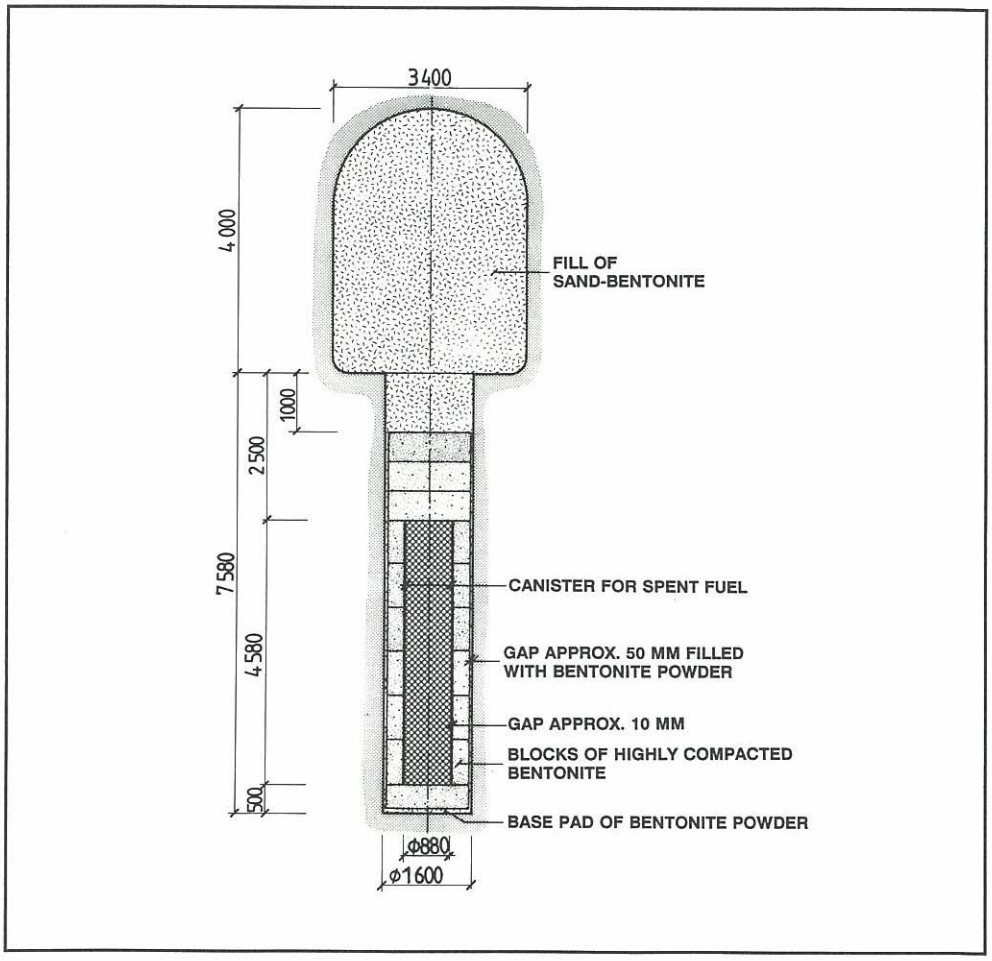


Figure B1-14. *Deposition hole with copper/steel canister and bentonite buffer – KBS-3.*

When the ramp has come down to repository depth and up to the central area under ground, the shaft is driven by means of conventional raise boring (boring of a pilot hole from the surface and reaming with a head from below).

The central area is excavation by means of conventional drilling-blasting technique.

Central tunnels and deposition tunnels are developed by means of the same technology.

The ventilation shaft at the end of the repository section is raise-bored.

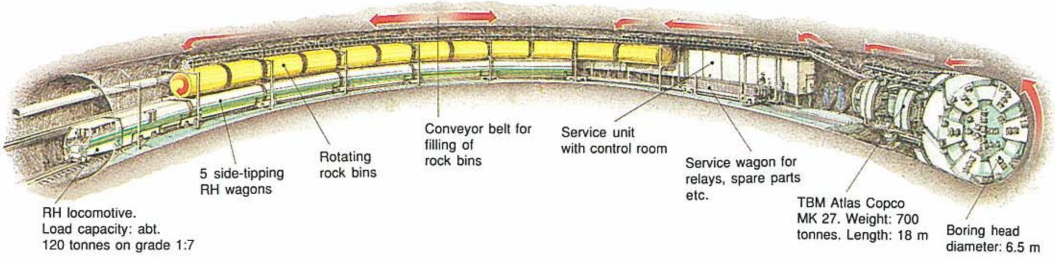


Figure B1-15. *Rapid Haulage System and the TBM-unit in Klippen. (Extract from brochure from Kraftbyggarna)*

The deposition holes have a diameter of 1.6 m (0.35 m thick bentonite buffer). Their depth is 7.6 m and their spacing is 6.0 m. Boring is started by drilling of a small pilot hole (about ø 150 mm) with a core drill in the centre. On the basis of this hole and its core, a judgement is made as to whether the position is suitable as a deposition site, considering the structure and permeability of the rock. If the verdict is positive, the hole is bored by means of full-face boring, whereby the pilot hole serves as a guide hole. Tamrock has specified equipment that would be suitable for this purpose in /B1-4/.

If the deposition site is not approved, the pilot hole is plugged. Nor are sites that are considered to be unsuitable after mapping of the locality used. Figure B1-16 illustrates the flexibility of the system.

4.3 DEPOSITION TECHNOLOGY

The canister is transported down in the ramp from the encapsulation plant in a radiation-shielded transport container, and up to the mouth of the deposition tunnel. There the canister is transferred to a deposition machine for handling of canisters and bentonite inside the deposition tunnel. The deposition sequence is illustrated in Figure B1-17.

The sequence begins with the covering of the bottom of the hole with bentonite, after which all ring-shaped bentonite blocks are placed in the hole and aligned by means of a dummy, if necessary.

The railbound electric deposition machine with canister is driven in. After a rough positioning of the vehicle at the deposition hole, hydraulic outriggers are put down and a fine adjustment of the position is carried out. The canister is raised to the upright position, lowered and released. A radiation shield on the deposition machine shields off the workplace from the transport tunnel.

A number of additional bentonite blocks are placed on top of the canister. Finally the hole is filled up with a bentonite-sand mixture and the tunnel is free for access. The hole is covered with a cap and a prop between the cap and the ceiling is fitted where necessary. The purpose of the prop is to prevent the bentonite from swelling out into the tunnel before the deposition tunnel has been backfilled.

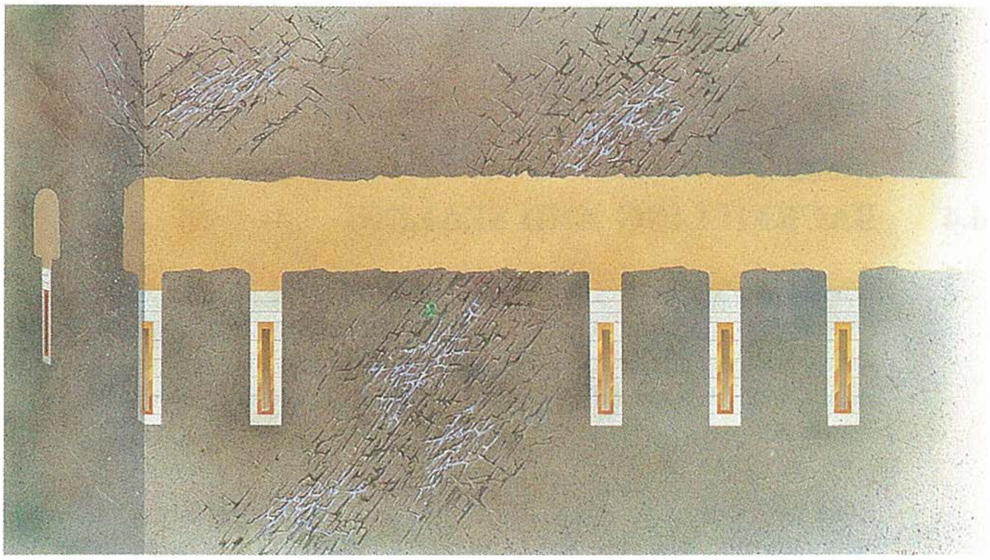


Figure B1-16. *Adaptation to varying rock conditions.*

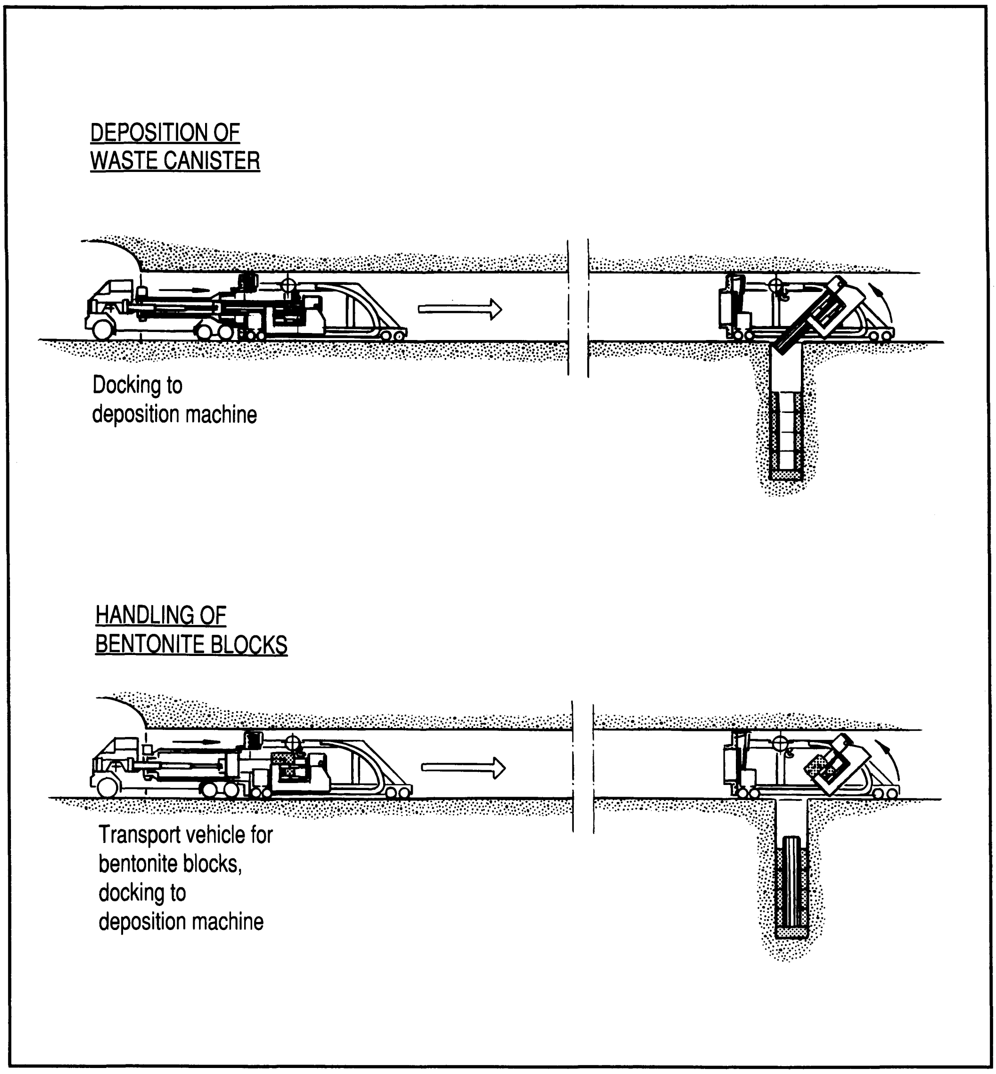


Figure B1-17. *Principle for deposition of canister and emplacement of bentonite buffer.*

4.4 BACKFILLING AND SEALING

When a number of deposition tunnels are finished the work of sealing them can begin. Provisional water drainage, props etc. are hereby removed and the tunnels are filled with sand/bentonite mixture. The tunnel mouths are sealed off with a provisional steel wall, which is removed in conjunction with backfilling of the central tunnel, see Figure B1-18.

After concluded deposition of all canisters, the entire facility is backfilled with bentonite-sand mixtures. The ramp and the shafts are hereby provided with plugs of compacted bentonite or concrete in certain sections. The purpose is to seal off and prevent water transport in channels that can be created axially along the chambers being bored or blasted out in the rock.

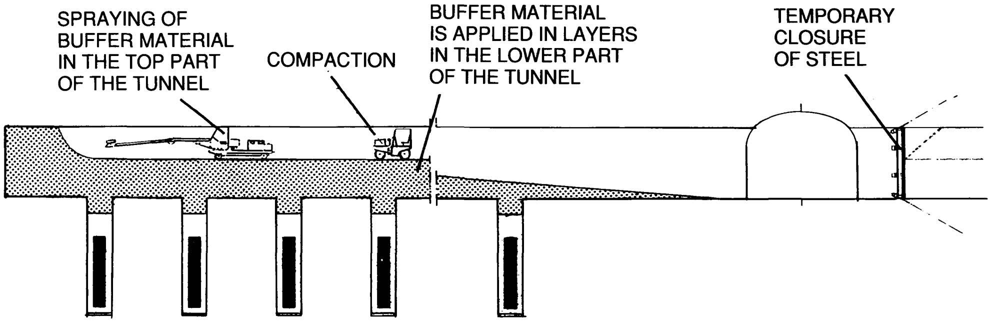


Figure B1-18. *Backfilling of deposition tunnel.*

5 DEEP REPOSITORY FOR LONG-LIVED LOW- AND INTERMEDIATE-LEVEL WASTE

Three different units are included in the total deep repository, but these have not been any part of the comparison and are therefore not described here. The only part that could be identified as a difference in certain cases is the section for the moulds with embedded BWR boxes, which will be omitted if the boxes are encapsulated together with the fuel. This difference only has a bearing on the cost analysis, but is so small that it has been neglected in the study.

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Encapsulation and handling of spent nuclear fuel for final disposal.
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June 1992
Description of Tamrock equipment for boring vertical deposition holes
SKB Arbetsrapport AR 92-40, Stockholm

Appendix 2

SYSTEM MEDIUM LONG HOLES, MLH

The appendix has been prepared for the purposes given in the body of the report.

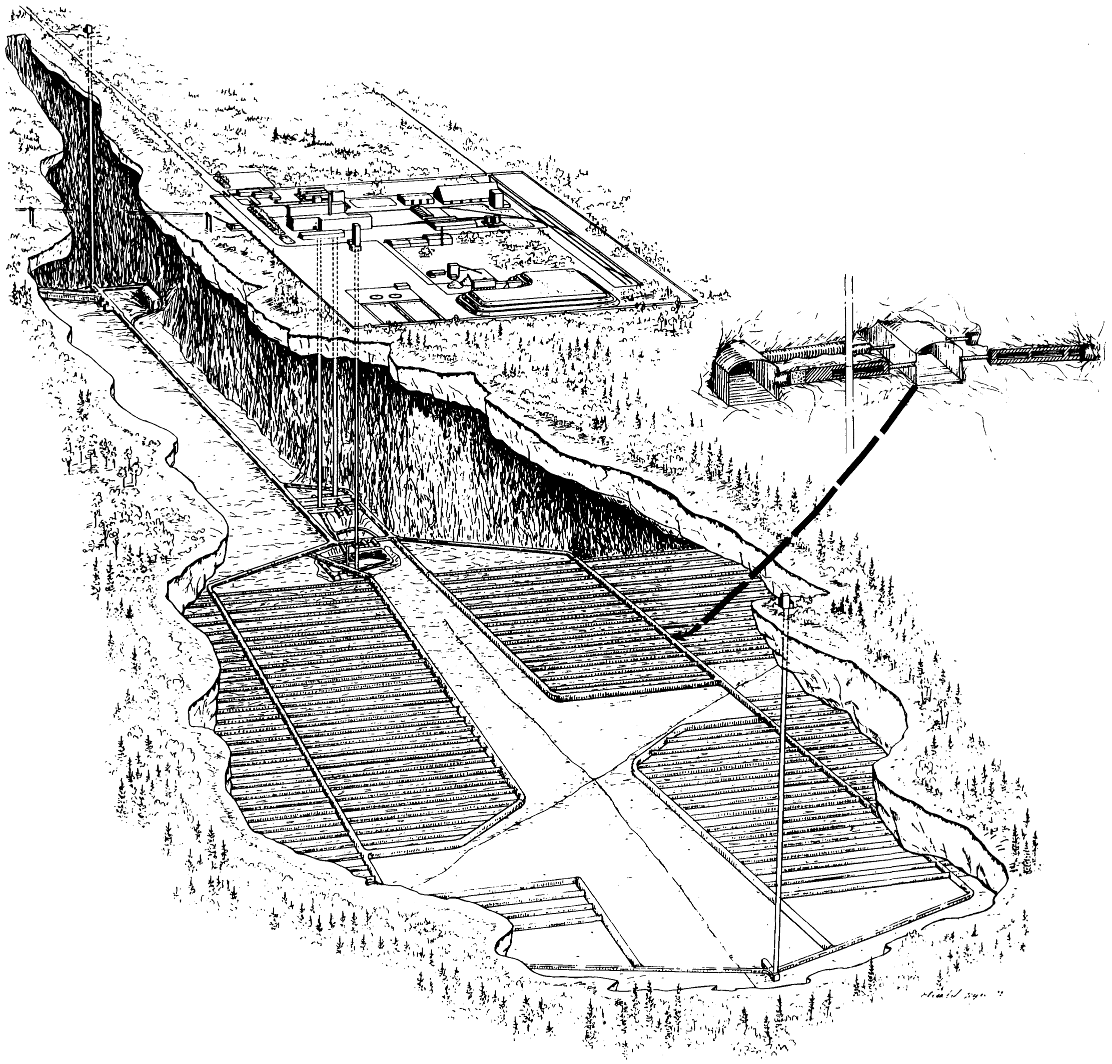

Figure B2-1. *Schematic drawing of MLH system.*

1 CANISTER ALTERNATIVES

The canister alternatives are the same as for KBS-3, see Appendix 1.

2 COMMON FACILITIES

These are also the same as for KBS-3, see Appendix 1, with the following exceptions:

The sand warehouse is not needed.

The rock pile is smaller.

3 ENCAPSULATION PLANT

This is identical with the one described for KBS-3, see Appendix 1.

4 DEEP REPOSITORY FOR SPENT NUCLEAR FUEL

4.1 DESIGN

The deep repository is assumed to be situated at a depth of 500 m below the ground surface. It is reached from the ground surface via a ramp (canisters and materials) and an elevator shaft (personnel).

The facility consists of a number of parallel deposition tunnels connected with a central tunnel and a side tunnel. In addition there are transport tunnels, service areas

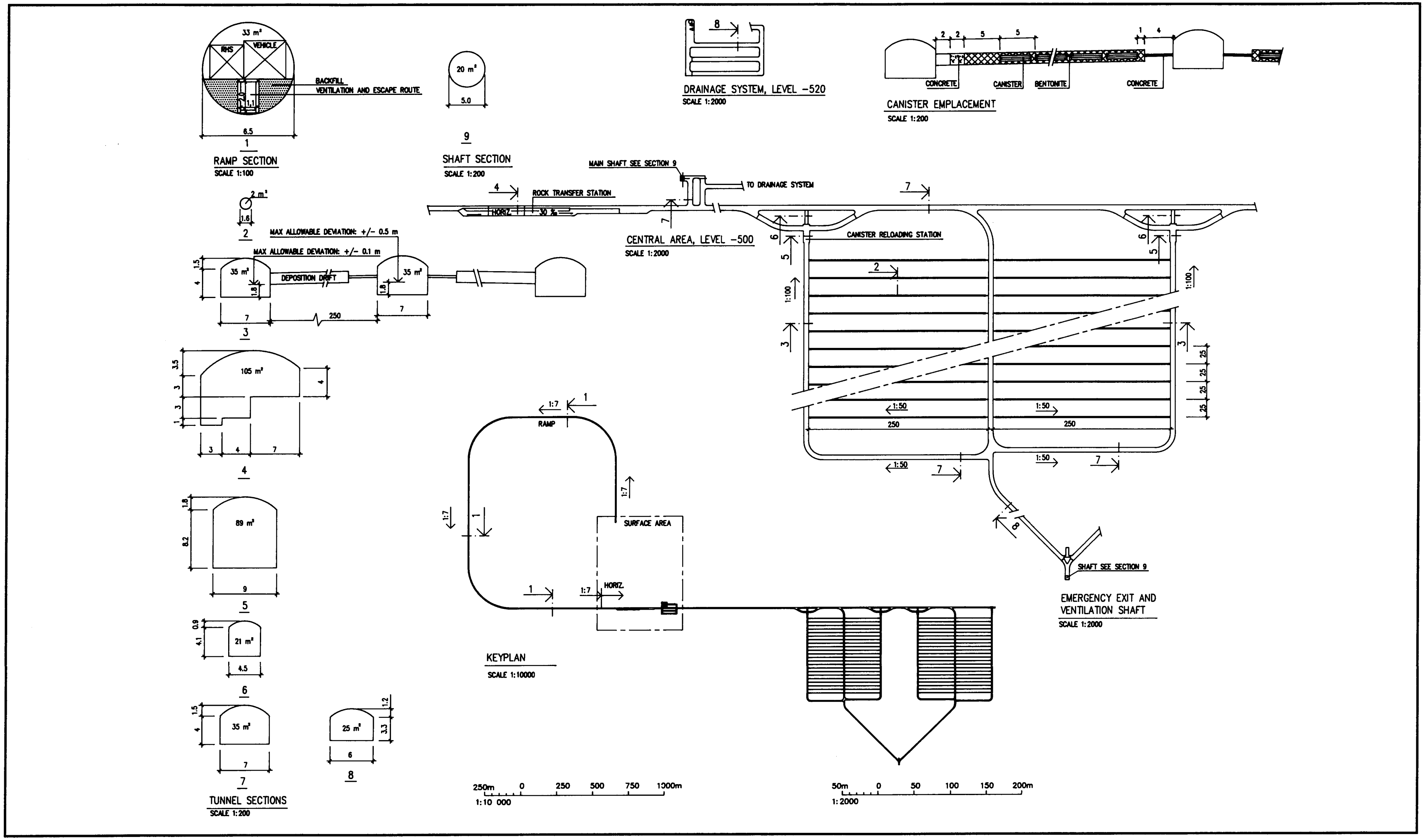

Figure B2-2 Schematic drawing of MLH system.

and a ventilation system, see the layout drawing in Figure B2-1. As for the KBS-3 system, the deposition area will be adapted to local conditions as far as the configuration and properties of the rock blocks are concerned. The extent of the facility will be determined primarily by the heat generation in the spent fuel.

The costs have been calculated for the layout shown in Figure B2-2.

The canisters are deposited horizontally in a row in the bored deposition tunnels.

The repository consists of a central section with service area and a deposition section. The central section in connected to the ground surface via a ramp and a shaft. The interior design and functions of the ramp and the shaft are the same as described under KBS-3, see Appendix 1 and Figure B2-2.

At the end of the repository section there is an exhaust air shaft that also serves as an evacuation shaft in emergencies.

During the deposition period the repository is divided into two parts to separate the deposition work from ongoing boring of deposition tunnels.

4.2 EXCAVATION TECHNOLOGY

The ramp down to the central area and the transport, central and side tunnels is bored or drilled/blasted as described in Appendix 1.

The deposition tunnels have a diameter of 1.6 m (copper/steel canister as per Figure B1-2a in Appendix 1, and 0.35 m thick bentonite buffer). They are bored by means of a special technology based on the method used in raise boring. In a first phase a pilot hole is drilled (ø 200–300 mm). Then the reaming head is put on and pulled towards the drilling rig. Drifts up to 4.0 m in diameter have been bored in this way. As a consequence of drilling deviations and bit wear, the length is assumed to be limited to 250 m.

The judgement of whether the route of the deposition tunnel runs through favourable rock can be made in several steps. The first step is to core-drill along the tunnel inside the tunnel contour. In the next step the pilot hole is drilled, providing supplementary information. In the last step the tunnel is reamed up, providing access for inspection of rock walls etc.

Rock support is expected to be used sparingly in the bored drifts.

4.3 DEPOSITION TECHNOLOGY

The canister is transported down in the ramp in a radiation-shielded transport container and further onto the deposition area. Here the package is lifted over from the transport vehicle to a deposition platform, see Figure B2-3. Previously the container with bentonite buffer has also been placed in position on the deposition platform. This platform also carries the deposition shuttle and the power and control unit.

Deposition is assumed to take place in two steps, whereby the entire bentonite buffer is emplaced in one step and the canister is pushed into the central hole in the a second step. The equipment assumed to be used in the study is described in /B2-1/.

The bentonite buffer is built up in the container in the underground service area. The bentonite consists of pressed blocks. A perforated liner with tolerance for insertion of the canister is left in the middle. The container with the pre-prepared bentonite buffer is pushed from the deposition platform into the deposition tunnel. The deposition platform moves in such a manner that the deposition shuttle comes into position for

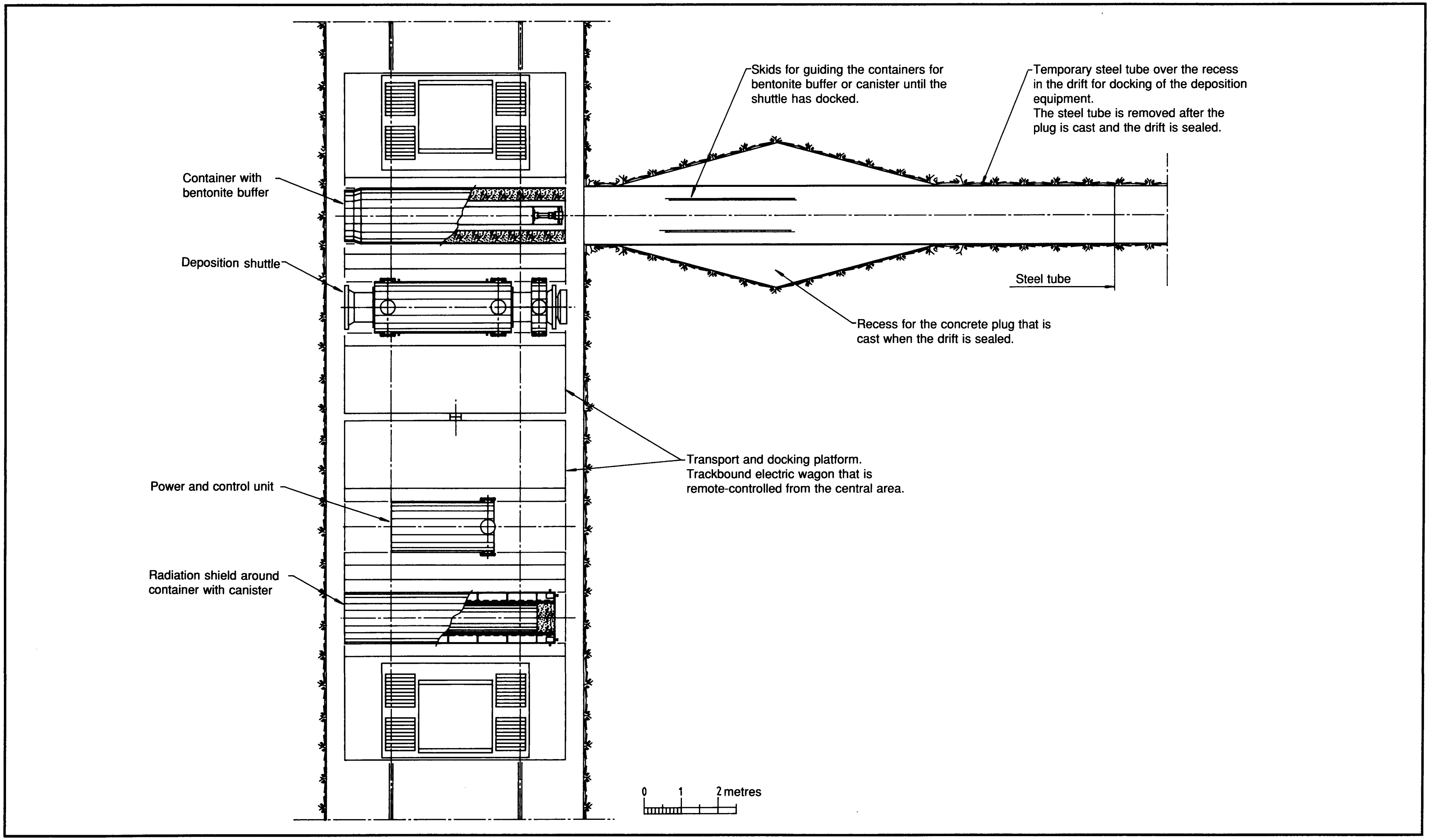

Figure B2-3. *Transport- and docking platform.*

the container, after which these two are docked and both are pushed into the tunnel. After another move of the deposition platform, the power unit is docked to the shuttle. The rig moves to the front. The shuttle carries the entire load and moves by paired detachment and advancement of feet that are pressed against the rock. This technique is used for TBMs.

At the front the container is lowered onto the floor of the tunnel and the container is withdrawn, leaving the bentonite buffer. The unit then moves backwards to the deposition platform.

The container with canister is then docked to the shuttle and transported into the bentonite buffer, where the canister is pushed into the liner. Finally, a bentonite plug is placed in the outer part of the liner.

In the event a section of the tunnel has been rejected for deposition, the central hole in the buffer is also filled with bentonite blocks.

4.4 SEALING

When a deposition tunnel has been filled, the mouth is plugged with a concrete plug. A sufficiently large bentonite plug is left against the concrete so that the concrete will not affect the bentonite around the nearest canister.

Temporary plugs may be needed for emplacement inside the deposition tunnels in the event prolonged interruptions must be made in the deposition work. The design of these plugs has only been summarily studied. It is assumed here that they can be designed for repeated installation/removal.

After concluded deposition, the entire deep repository is filled with bentonite-sand mixture. Potential transport pathways for groundwater are cut off by means of plugs in the same way as in the KBS-3 system, see Appendix 1.

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April 1992
PASS – Method for horizontal emplacement of KBS-3 type canisters in 1.6 m diameter drifts
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SYSTEM VERY LONG HOLES, VLH

The appendix has been prepared for the purposes given in the body of the report.

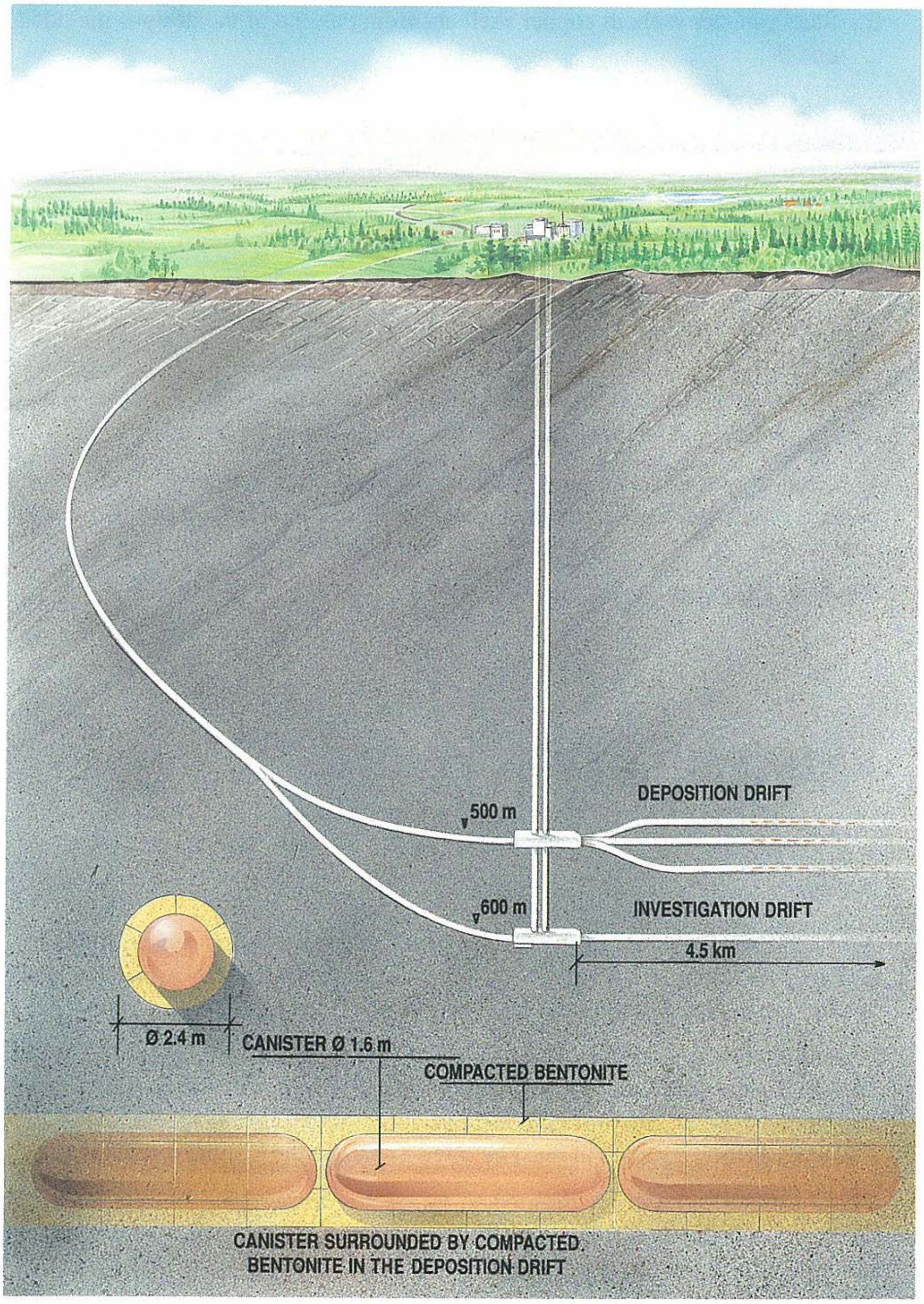


Figure B3-1. *Schematic illustration of the VLH system.*

1 CANISTER ALTERNATIVES

The canister alternatives that have been analyzed are:

A. Copper/steel canister with hemispherical ends, see Figure B3-2a and b.

B. Copper/steel canister with flat ends, see Figure B3-3.

C. Steel canister without copper shell according to one of the designs included in A and B.

2 COMMON FACILITIES

These are the same as for the KBS-3 system, with a few exceptions. Compared with the description in Appendix 1, the following is changed for VLH:

The sand warehouse is not needed, since the backfilling volume is small and attributable to central sections etc., which are only backfilled when all deposition has been concluded.

The rock pile on the surface is smaller.

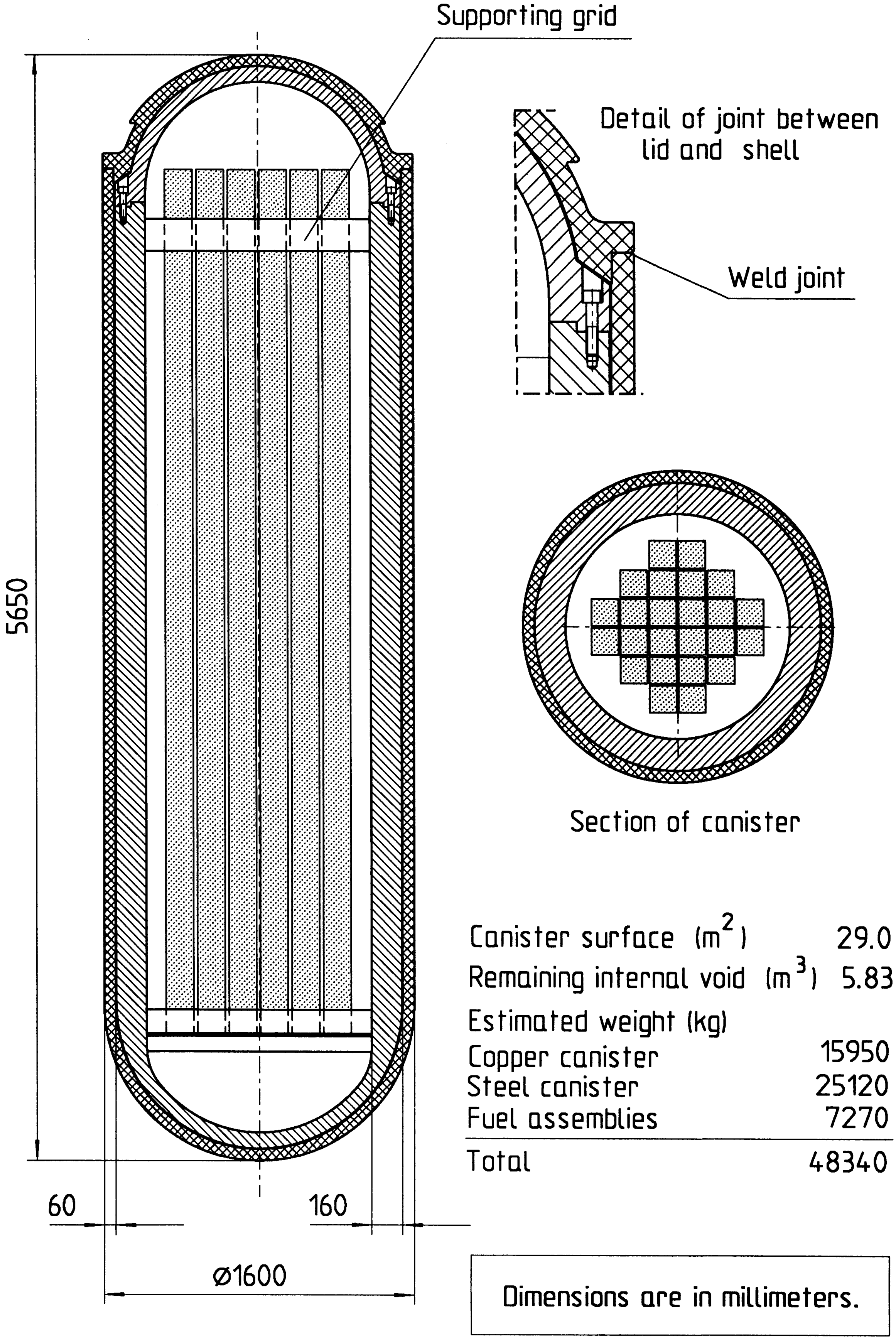
3 ENCAPSULATION PLANT

All necessary functions in the encapsulation plant needed for encapsulation of the composite canister in the KBS-3 system (see the description in Appendix 1) are also needed for encapsulation of the VLH canister.

There are, however, certain differences in consequence of the heavier VLH canister. Docking openings to the hot cell must be made bigger, as must the radiation shield around the canister. The welding cell must have dimensions to accommodate the large diameter. Lifting equipment must be rated to handle the heavier weight, etc.

These differences are not deemed to be of any importance from a technical and safety-related viewpoint. Their effect on cost is also small but has been recognized in the calculations.

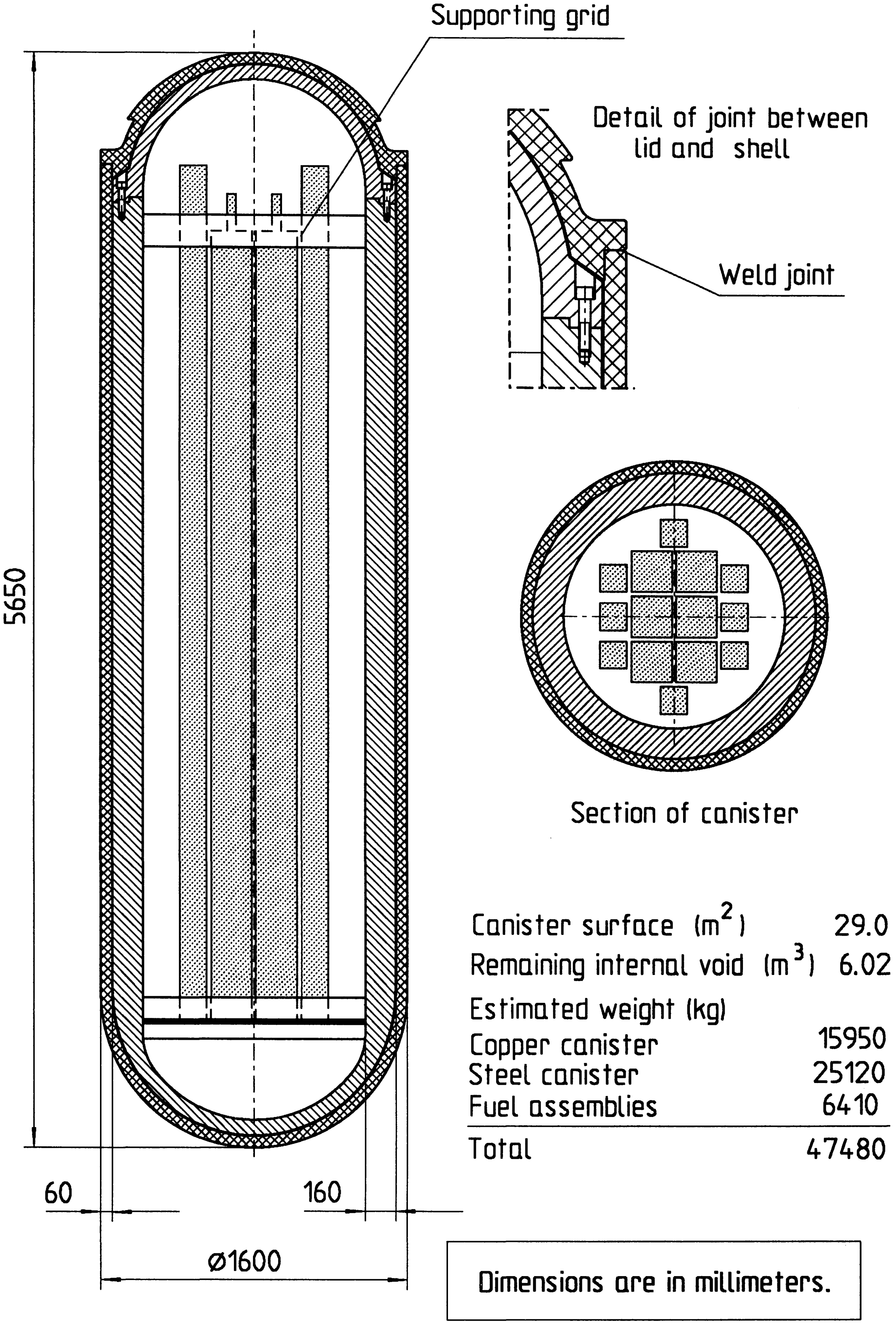
The capacity of the encapsulation plant is just as large as the one in KBS-3 figured in tonnes of spent fuel. Since each canister contains twice as much fuel as the KBS-3 canister, this means that one canister is finished every other day on average.



Canister surface (m^2)	29.0
Remaining internal void (m^3)	5.83
Estimated weight (kg)	
Copper canister	15950
Steel canister	25120
Fuel assemblies	7270
Total	48340

Dimensions are in millimeters.

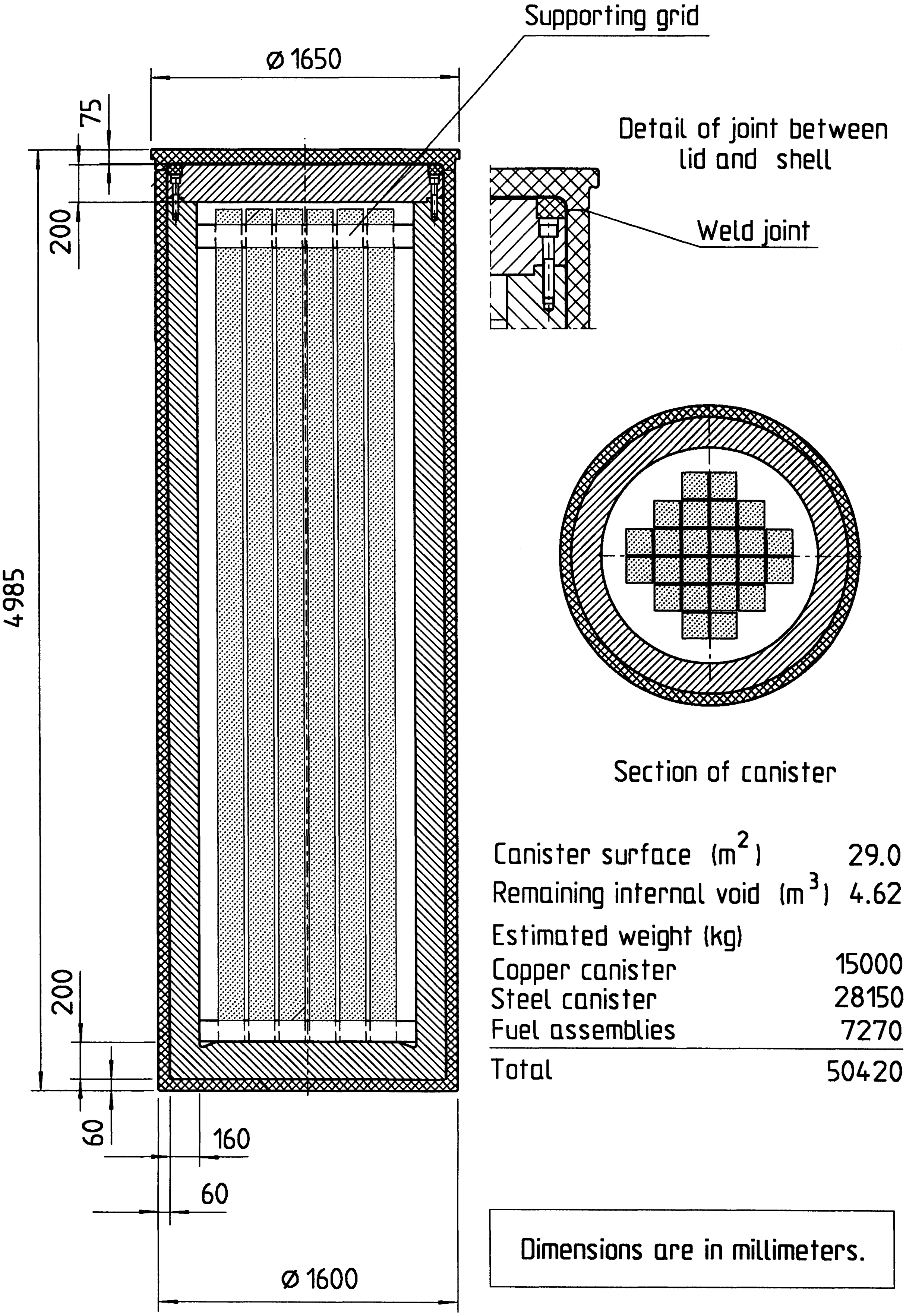
Figure B3-2a. *Copper/steel canister with hemispherical ends, BWR assemblies.*



Canister surface (m^2)	29.0
Remaining internal void (m^3)	6.02
Estimated weight (kg)	
Copper canister	15950
Steel canister	25120
Fuel assemblies	6410
Total	47480

Dimensions are in millimeters.

Figure B3-2b. *Copper/steel canister with hemispherical ends, PWR assemblies.*



Canister surface (m^2)	29.0
Remaining internal void (m^3)	4.62
Estimated weight (kg)	
Copper canister	15000
Steel canister	28150
Fuel assemblies	7270
Total	50420

Figure B3-3. *Copper/steel canister with flat ends, BWR assemblies.*

4 DEEP REPOSITORY FOR SPENT FUEL

4.1 DESIGN

The deposition section of the deep repository differs considerably from the KBS-3 repository. It is, however, located at the same assumed depth, 500 m below the surface, and is reached via ramp with a gradient of 1:7, plus vertical shafts for personnel transports, ventilation etc. A drawing of the presumed detailed design is shown in Figure B3-4.

Below the repository level, at a depth of about 600 m, is an investigation tunnel that serves as the probe tunnel for determining the final position of the deposition tunnels.

The repository consists of a central section and a deposition section. The central area is sized to accommodate the required deposition equipment and the handling of muck that is produced. The central area is reached from the ground surface via a ramp and a service shaft. Their interior design and functions are the same as described in Appendix 1. The difference in the ramp is that the canister with transport shield is bigger.

The deposition area consists of three parallel, horizontal tunnels spaced at a distance that limits the interaction between the tunnels, especially the temperature influence. The canisters are placed in the centre of these tunnels, as shown schematically by Figure B3-1.

Deposition has to take place in two of the tunnels in parallel at the beginning, when the distance to the front is great. These tunnels are kept separate from the third tunnel, which is still being driven during the initial stage.

4.2 EXCAVATION TECHNOLOGY

Ramp, shaft and central area are excavated in the same manner described in Appendix 1.

The investigation tunnel at a depth of 600 m, as well as the three deposition tunnels, are drilled using the TBM method. A number of references exist for boring tunnels with different diameters in hard rock. The subject is examined in /B3-1/.

It is believed likely that the tunnels will intersect major fracture zones unsuitable for deposition of canisters, see Figure B3-5.

4.3 DEPOSITION TECHNOLOGY

The canisters in radiation-shielding transport casks are hauled down to the repository on the ramp by, for example, RHS trains, see Figure B1-15 in Appendix 1. The transport is driven all the way up to the service area at the mouth of the deposition tunnel, where the deposition units are waiting. There the canister is lifted or pushed out of the transport cask and laid in the deposition vehicle. The canister is no longer surrounded by any radiation shield. A schematic drawing of the service area is shown in Figure B3-6.

Deposition proceeds as follows: A bentonite bed is laid out, the canister is placed on this bed and the other blocks are placed in position. The procedure and equipment assumed in the study are described in /B3-2/.

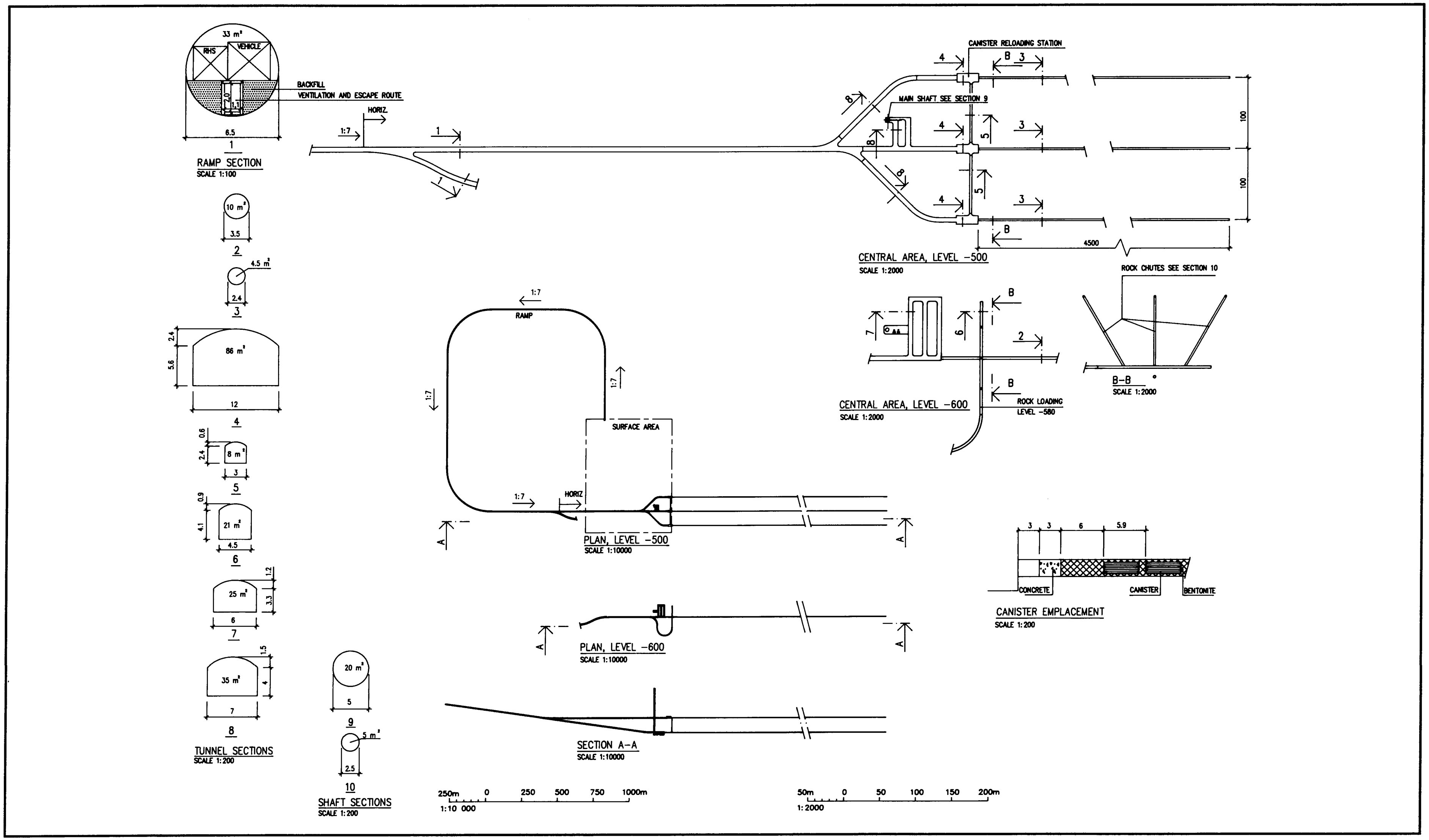


Figure B3-4. Base for cost calculations – VLH.

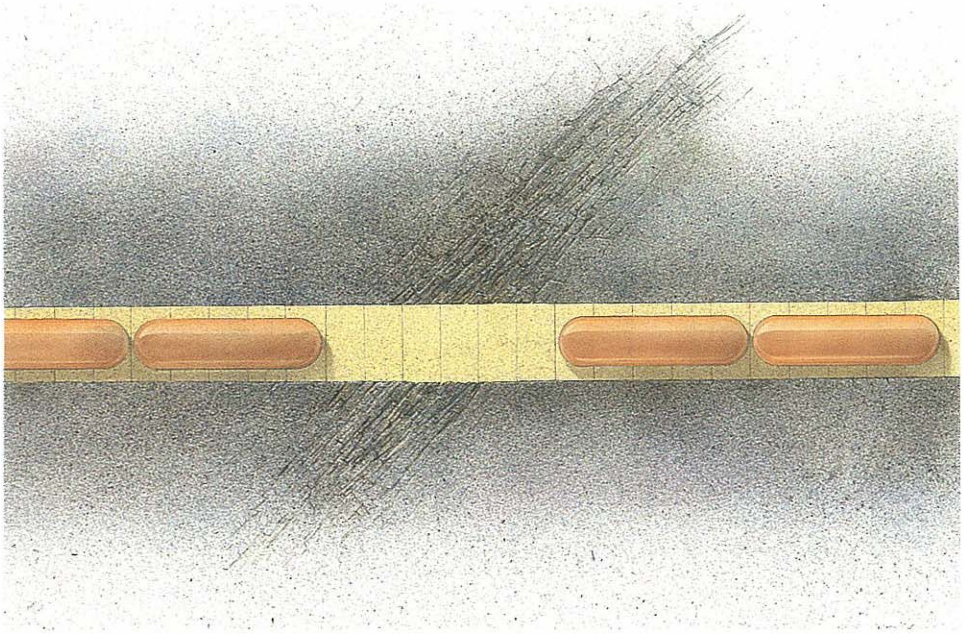


Figure B3-5. *Adjustment to varying rock conditions.*

Figure B3-7 shows the number of blocks that will be placed around each canister. The blocks weigh up to about 900 kg apiece, which is judged to be a possible size to fabricate without any troublesome stresses being created in the blocks.

Figure B3-8 shows the deposition sequence. In Step 1 a trackless "wagon" with bentonite manipulator I and a trailer loaded with blocks for a–d in Figure B3-8 drives up to the front and delivers the blocks in the sequence shown. The manipulator and the handler of the blocks from the trailer are completely remote-controlled and certain movements could possibly be made automatic. The wagon then backs out of the tunnel. In Step 2 the "wagon" with the canister drives up to the deposited bentonite bed. The appearance of the wagon is shown by the drawing in Figure B3-9. The front forks are folded out when the rig arrives at the front and they straddle the deposited

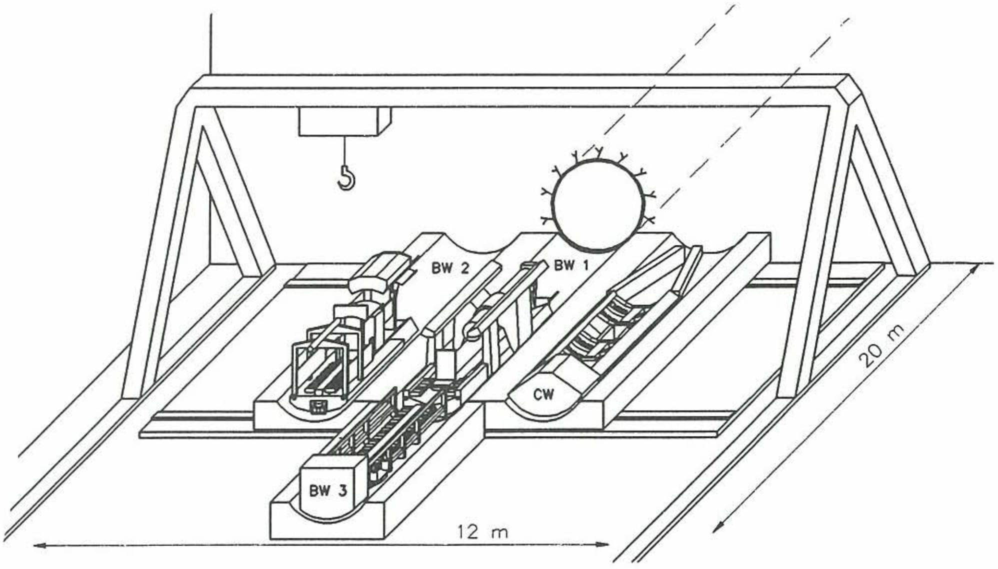


Figure B3-6. *Service area at the mouth of a deposition drift, CW = Canister Wagon and BW = Bentonite Wagon.*

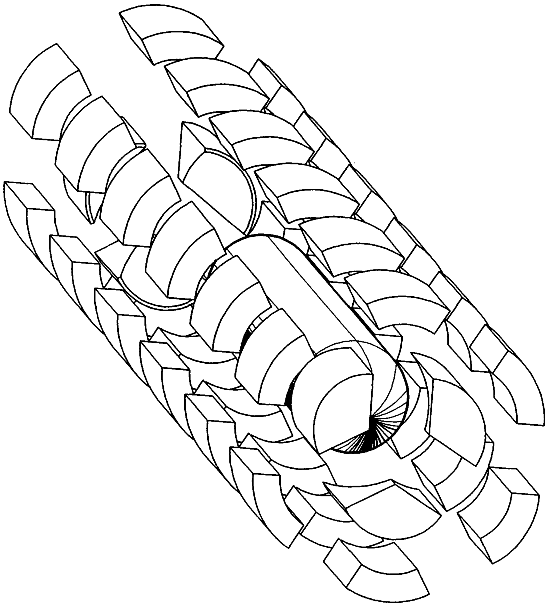


Figure B3-7. *Bentonite blocks per canister position.*

bentonite bed. The canister is then moved forward by means of repeated up-forward-down movements until it only lies on the forks, after which the forks are lowered and the canister is placed on the bentonite bed. The "canister wagon" then back out to the service area. Finally, in Step 3, a "wagon" with bentonite manipulator II and trailer with the blocks for f and g (see Figure B3-8) drives up to the deposited canister and lays block after block in place.

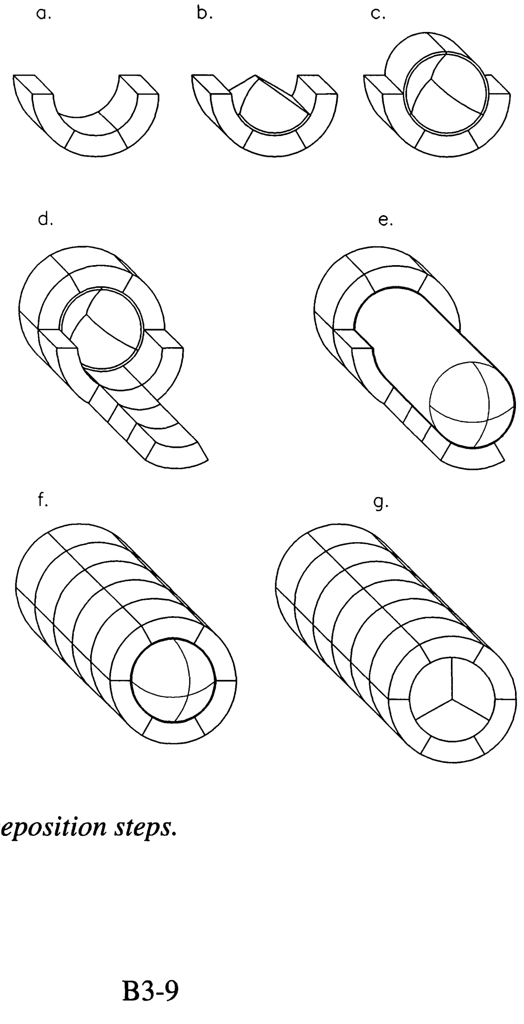


Figure B3-8. *Deposition steps.*

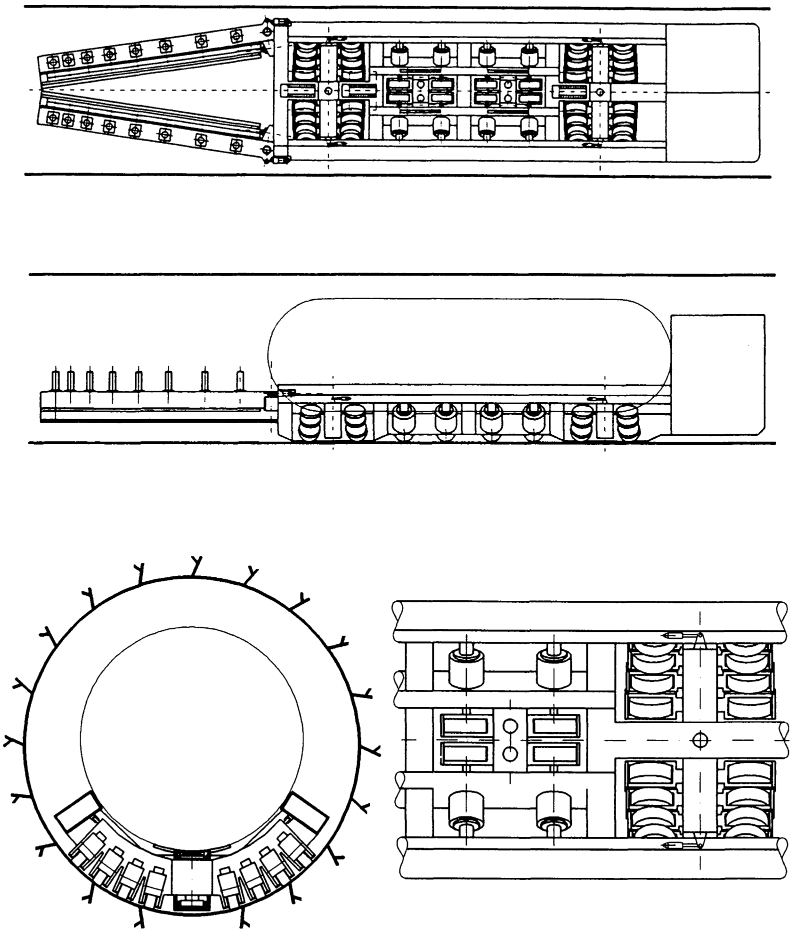


Figure B3-9. *Trackless wagon for deposition of canister. The upper figure shows a wagon with forks. They are equipped with a conveyor that can be raised and lowered for moving the canister from the transport position to the deposition position. The lower Figure shows details of the bogie system.*

Canisters with flat ends offer a somewhat simpler method of block handling, since the concave blocks can then be avoided.

In the event of a prolonged stoppage or planned pause, a plug – permanent or temporary – must be installed against the most recently deposited canister. Such structures have not been studied. It is here assumed that structures that are possible to mantle/dismantle may be developed.

4.4 SEALING

When a tunnel has been filled the tunnel mouth is sealed off with a combined concrete/bentonite plug. The design is the same as planned for vertical shafts.

When all canisters are in place, all excavations under ground, including the investigation tunnel at a depth of 600 m, are backfilled with bentonite-sand mixtures. The ramp and the shaft are provided with more qualified plugs in certain sections, see Appendix 1.

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SKB Technical Report TR 92-16.

SYSTEM VERY DEEP HOLES, VDH

The appendix has been prepared for the purposes given in the body of the report.

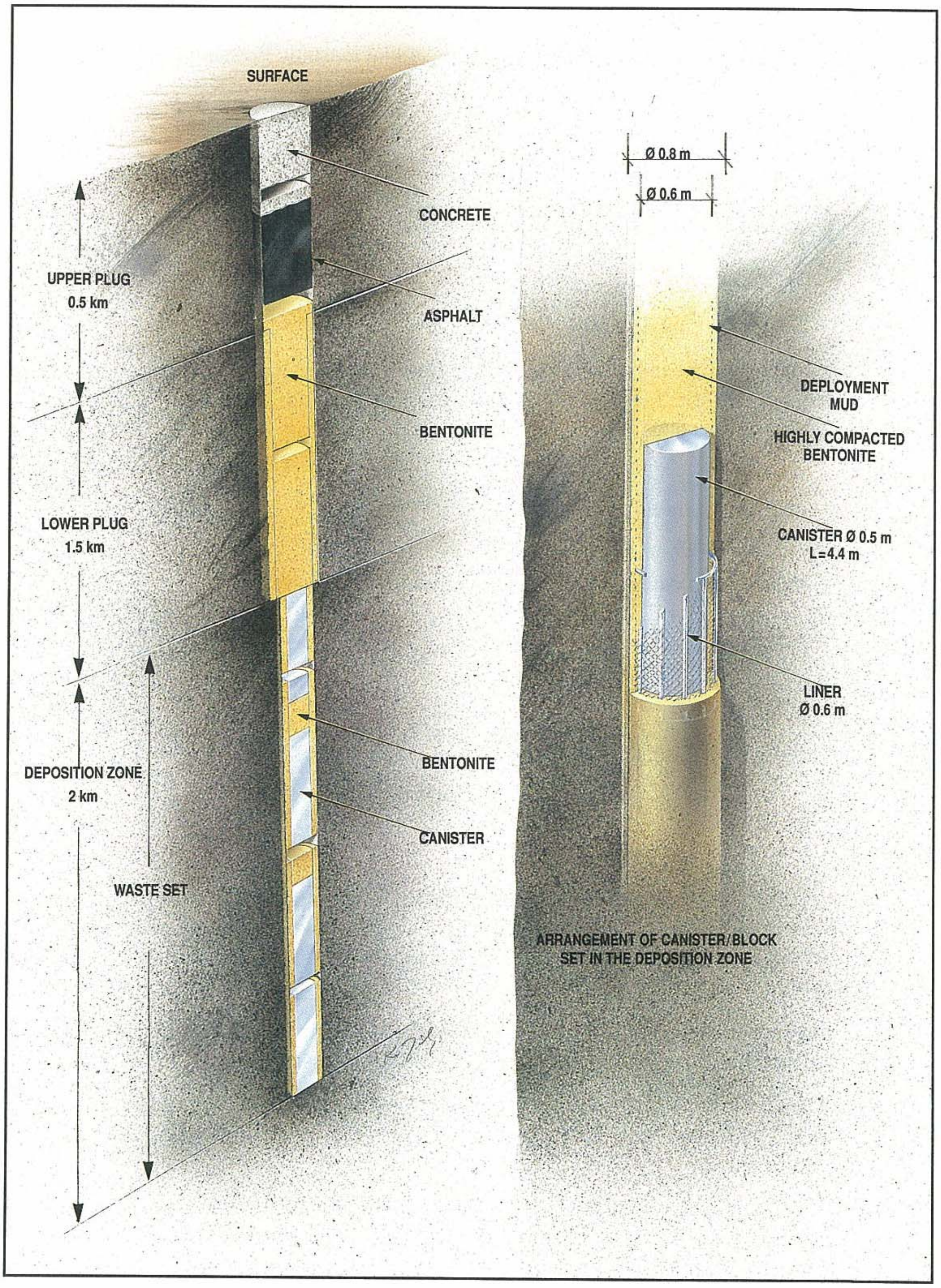


Figure B4-1. *Schematic drawing of VDH system.*

1 CANISTER ALTERNATIVES

The canister alternatives that have been analyzed are:

A. Titanium canister with concrete fill, see Figure B4-2 (intact BWR assemblies and consolidated assemblies);

B. Copper canister fabricated by means of Hot Isostatic Pressing (HIP).

2 COMMON FACILITIES

Co-siting of the encapsulation and the deep repository mean that transports are not required for the VDH system to the same extent as for other studied systems. The industrial area does not contain:

- rock pile
- surface buildings over shafts
- access ramp
- ventilation equipment for the underground portion.

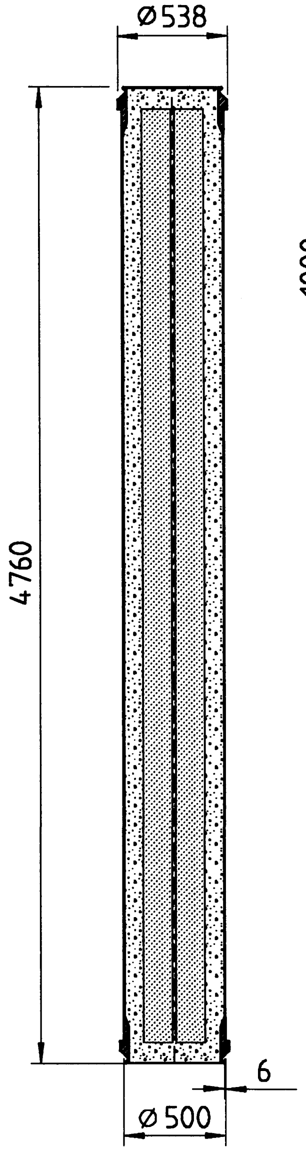
3 ENCAPSULATION PLANT

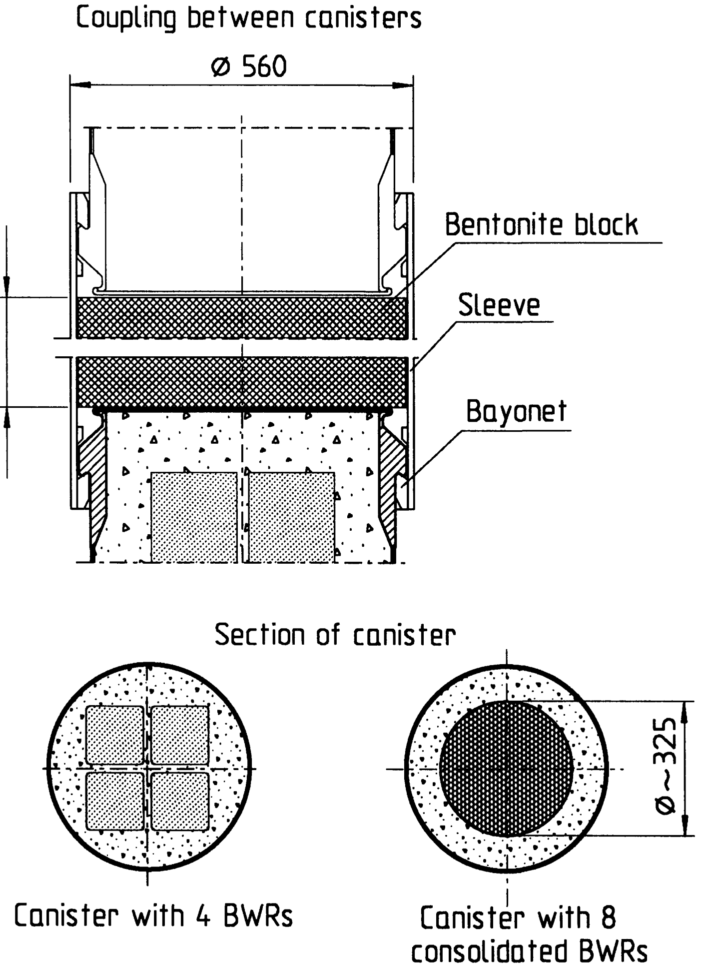
The analysis has been concentrated primarily on the concrete-filled titanium canister. The perspective drawing in Figure B1-8, Appendix 1, gives a good idea of the appearance of the building. The differences for the VDH canister are in details that pertain to the special design of the canister.

Capacity is sized for a production rate of three canisters per day with non-consolidated assemblies and 1.5 canisters with consolidated assemblies.

It is assumed that the boxes are separated from the assemblies before they are inserted into the canister. Note that Figure B4-2 gives the length dimension for assemblies "with boxes".

Handling of the spent fuel is illustrated by the flow schemes in Figure B4-3 (non-consolidated assemblies) and Figure B4-4 (consolidated assemblies). In comparison with the scheme for the KBS-3 canister (see Figure B1-10 in Appendix 1), these undergo completely different handling in the "hot cell" and the "welding cell". These parts have not been studied in as great detail as the plant sections for KBS-3 canisters. The





Canister surface (m^2) 7.87

Estimated weights (kg)

	4 FA	8 con.
Titanium	210	210
Concrete filling	1640	1390
Fuel assemblies	1210	2050
Total	3060	3650

Dimensions are in millimeters.

Figure B4-2. *Titanium canister with concrete filling.*

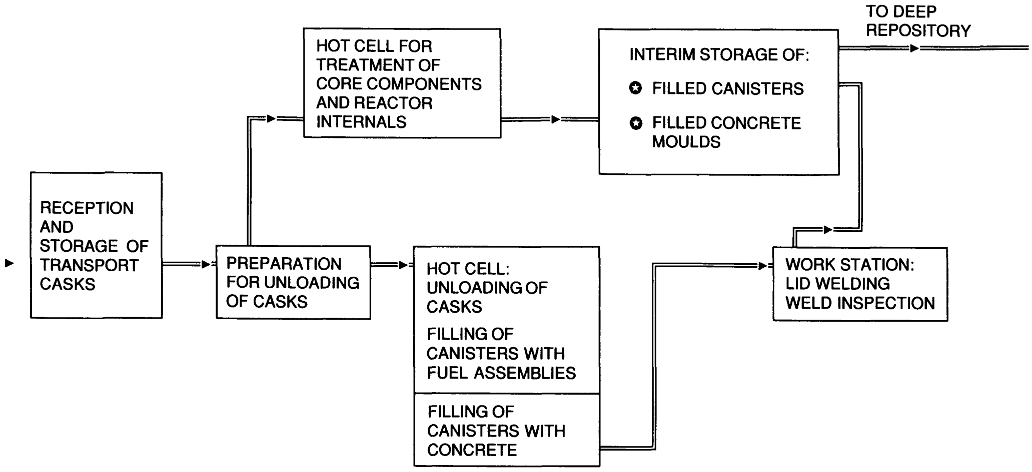


Figure B4-3. Flow scheme for encapsulation of nonconsolidated assemblies

encapsulation of non-consolidated assemblies is not, however, assumed to differ in terms of function from the encapsulation in KBS-3.

Non-consolidated assemblies

After the fuel assemblies have been lowered into the titanium shell the canister is transferred to a special cell where it is filled with concrete.

When the concrete has cured, the canister is transferred to the "welding cell", where the top surface of the cement is first evened off before the lid is put on and welded down.

Consolidated assemblies

In this alternative, the cell for unloading of the transport casks contains units for dismantling of the fuel assemblies and consolidation of the rods so that they fit in a special container, which after sealing is lowered into the canister.

The canister is then filled with cement and welded shut in the same way as in the process for the canister with non-consolidated assemblies.

Other metal parts are compacted in a special cell and encapsulated in separate canisters of the same type as those used for the fuel itself.

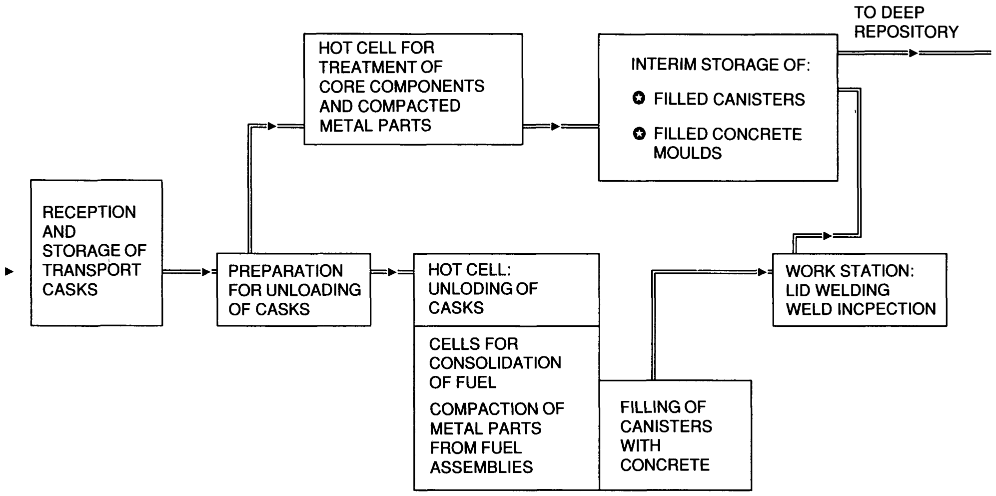


Figure B4-4. Flow scheme for encapsulation of consolidated assemblies.

4 DEEP REPOSITORY FOR SPENT NUCLEAR FUEL

4.1 DESIGN

The VDH system is described in detail in /B4-2/. A schematic division of a borehole into deposition and plugging zones is shown in Figure B4-1. The sections of the borehole that run through highly water-bearing zones are not intended to be utilized for deposition. These sections are filled with bentonite alone.

The deep repository consists of a number of deep boreholes spaced 500 m apart. A workplace is required at each drilling position with room for drilling rig, sheds, workshop and mud handling. Figure B4-5 shows a schematic drawing of a deposition area with 19 boreholes (consolidated assemblies) or 38 boreholes (non-consolidated assemblies). The area covers about 3 km or 7 km, respectively, if the boreholes are positioned as shown in the figure.

Roads and utility lines for electricity, water supply and drainage etc. are run to each drilling position.

4.2 EXCAVATION TECHNOLOGY

The drilling is based on oil well drilling technology and the additional experience gained from the deep borehole at Gravberg.

It is assumed that the borehole will be 0.8 m in diameter in the deposition section, which is the largest diameter deemed possible today to be drilled to a depth of 4 km.

Drilling is done with a bentonite mud as drilling fluid at depth. The required casing is made of a bronze grade instead of the steel grade used within the oil industry. In this way reducing corrosion with hydrogen gas formation is avoided. The casing is made sufficiently perforated so that the bentonite can fill out the entire "void" in the borehole around the canister.

4.3 DEPOSITION TECHNOLOGY

One possible method for depositing the canisters is described in /B4-2/. The method is only roughly sketched and is based on the use of the same rig as that used for the drilling. The principle is that the canister is fastened to the drill bit's position on the drill pipe and pushed down in the liner to the deposition position.

Before deposition starts in a borehole, the bentonite drilling mud that is used during drilling is replaced by a thicker bentonite deployment mud, as thick as can be permitted in view of the fact that the canister must be pressed down through the mud without being damaged. Two or more canisters with intervening highly compacted bentonite blocks are connected together into a string that is pushed down all at once. The bentonite proportion is adjusted so that the average bentonite density is high enough and sufficient for the bentonite to hold each canister in place when it swells. Checking of the canister's position in the hole is important, and it is believed this can be done with the aid of methods and instruments developed in the oil well drilling

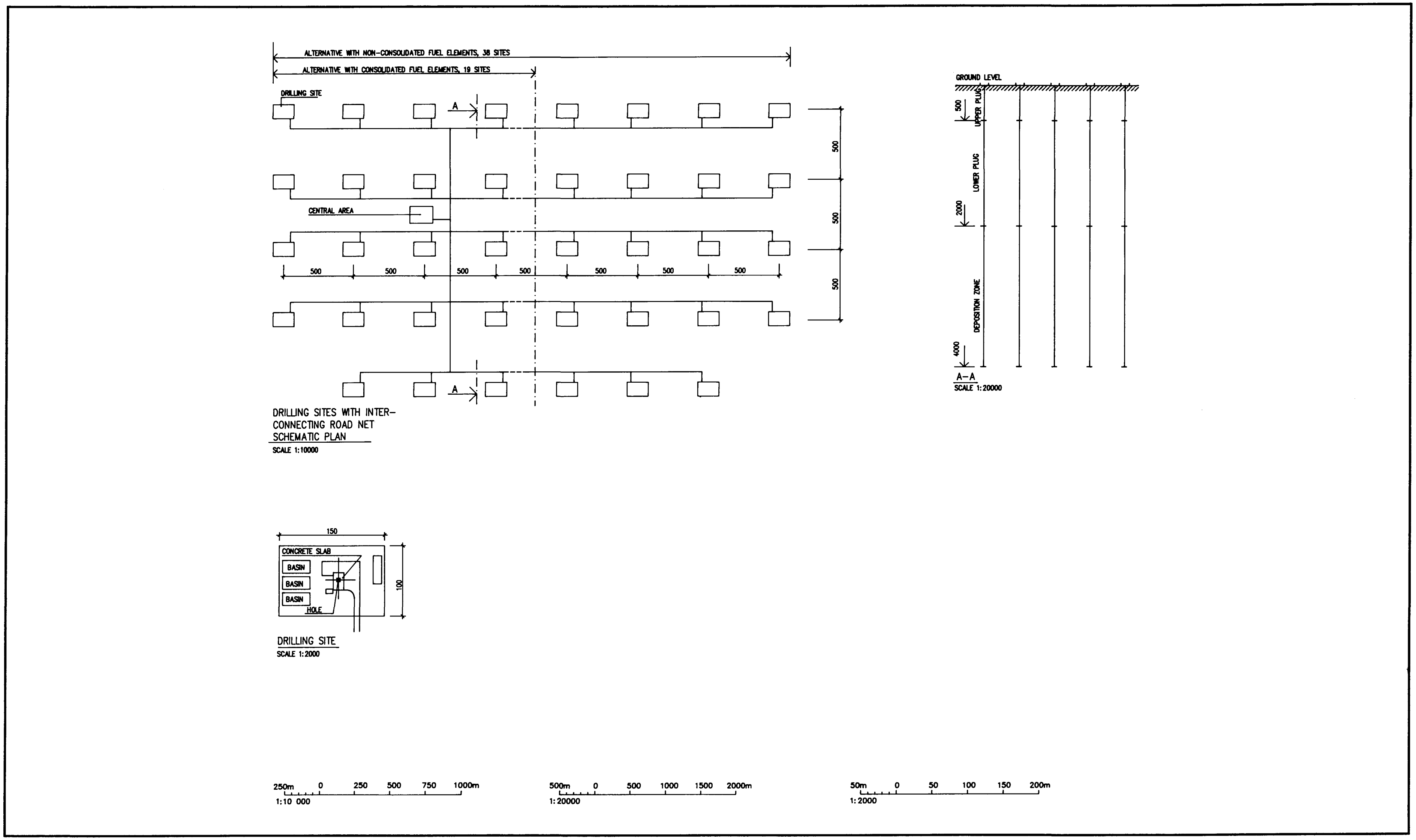


Figure B4-5. *Base for cost calculations – VDH.*

industry. It is believed that a suitable deposition (deployment) rate is about 200 m of borehole per month and hole.

4.4 SEALING

The uppermost 2 000 m of the hole are plugged to prevent axial water transport along or in the borehole. At one or more points along the borehole, "windows" can be milled that cut off the disturbed zone (if any) around the hole.

Two different plugging sections can be distinguished. The lower section, from 2 000 to 500 m depth, is filled with compacted bentonite blocks inside the perforated casing. The blocks are pushed down in as thick bentonite mud as possible. The upper part, from 500 m depth to the surface, is filled up with asphalt. This is capped with a concrete plug.

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B4-2 Juhlin C, Sandstedt H
December 1989
Storage of nuclear waste in very deep boreholes: Feasibility study and assessment of economical potential
SKB Technical Report TR 89-39

PAIRWISE COMPARISONS WITH THE ANALYTIC HIERARCHY PROCESS (AHP)

1 PRINCIPLES OF THE METHOD

AHP includes, by definition, a **problem structuring**, a **pairwise comparison** and a mathematical evaluation /B5-1/.

1.1 PROBLEM STRUCTURING

The principle of structuring is that the problems are organized in hierarchical levels in the same way as is described in chapter 4 in the main text, see Figure B5-1.

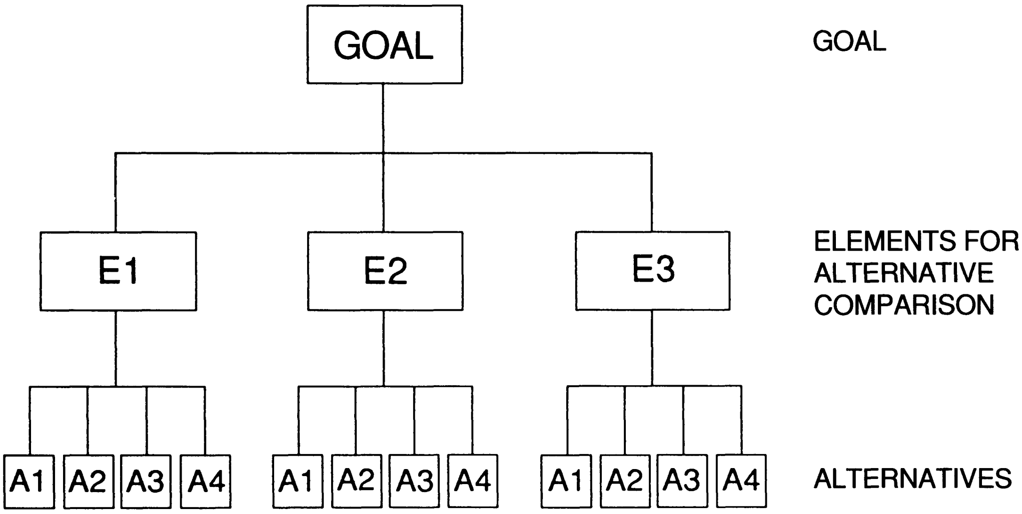


Figure B5-1. *Principle for hierarchical structuring.*

1.2 PAIRWISE COMPARISON

The principle is to make a comparison of the elements (alternatives) for each level with respect to how essential they are for an element on the next higher level. This facilitates the comparison, since each time it focuses on a limited part of the whole problem.

The result is a series of pairwise comparisons that can then be combined.

A nine-point scale that can be expressed verbally or numerically is used in the comparison.

The scale is reproduced below in its original form.

Numerical scale	Verbal scale
1.0	Equal importance of both elements
3.0	Moderate importance of one element over another
5.0	Strong importance of one element over another
7.0	Very strong importance of one element over another
9.0	Extreme importance of one element over another
2.0; 4.0; 6.0; 8.0	Intermediate values between two adjacent judgements

1.3 EXAMPLE

To illustrate the method, an example is presented that is a part of the main structure in the comparison given by the expert group.

2 PROBLEM STRUCTURING

The hierarchical model in the example contains the following elements, see also Figure B5-2:

Elements on level 1	Elements on level 2	Alternatives
TECHNICAL FEASIBILITY	CONSTRUCTION	KBS-3, MLH, VLH, VDH
	DEPOSITION/ SEALING	KBS-3, MLH, VLH, VDH
HUMAN INTRUSION		KBS-3, MLH, VLH, VDH

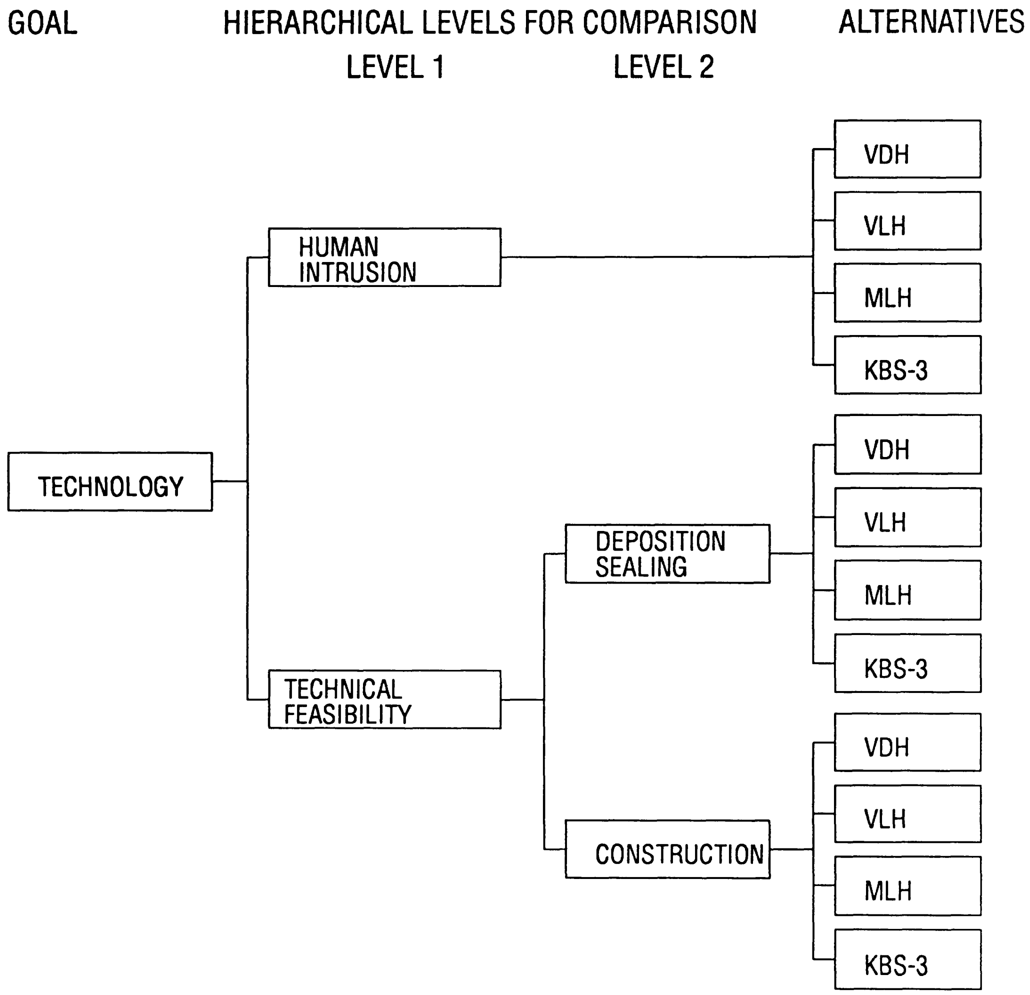


Figure B5-2. *The hierarchical structure in the example.*

3 PAIRWISE COMPARISON

The comparison is done from the top down here.

A. First TECHNICAL FEASIBILITY is compared with HUMAN INTRUSION with respect to the next higher level, i.e. the goal.

The expert believes that TECHNICAL FEASIBILITY is 3 times (slightly more) more important than HUMAN INTRUSION.

In matrix form we get:	TECHNICAL FEASIBILITY	HUMAN INTRUSION
TECHNICAL FEASIBILITY	1	3
HUMAN INTRUSION		1

B. Then on the next level, DEPOSITION/SEALING is compared with CONSTRUCTION with respect to TECHNICAL FEASIBILITY (not the GOAL!)

The expert believes that both are equally important:

	CONSTRUCTION	DEPOSITION/ SEALING
CONSTRUCTION	1	1
DEPOSITION/ SEALING	1	

Then the different alternatives are compared with respect to the criterion on the next higher hierarchical level. We thus get three such comparisons, with respect to HUMAN INTRUSION, DEPOSITION/SEALING and CONSTRUCTION.

The expert is assumed to make the following judgement with respect to CONSTRUCTION:

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

In the table, 1/3 means that the alternative in the column is 3 times more preferable than the value on the line to the left, i.e. the expert prefers VLH to both KBS-3 and MLH. Moreover, the expert believes that VLH is 5 times more preferable than VDH. The reciprocal values are written in the empty matrix points during the evaluation.

4 CALCULATION SEQUENCE DURING EVALUATION

The evaluation is done starting from the top.

First TECHNICAL FEASIBILITY and HUMAN INTRUSION are compared with respect to GOAL. The expert's ratings are set up in matrix form. The values are then normalized by summing up each column.

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

Each element is then divided by the corresponding column sum, and in the new matrix the rows are numbered.

Finally the relative weights (with respect to GOAL) are obtained by means of averaging by dividing the row sums with the number of elements in the row, in this case 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

The same procedure is then followed on the next lower level:

CONSTRUCTION is compared with DEPOSITION/SEALING with respect to the level above, in this case TECHNICAL FEASIBILITY.

	CON-STRUCTION	DEPOSITION/ SEALING
CON-STRUCTION	1	1
DEPOSITION/ SEALING	1	1
Column sum	2	2

	CON-STRUCTION	DEPOSITION/ SEALING	Row sum	Weight
CON-STRUCTION	0.5	0.5	1	0.5
DEPOSITION/ SEALING	0.5	0.5	1	0.5

Finally, on the lowest level the different alternatives are compared with respect to CONSTRUCTION. (The calculations below have been carried out to more than three decimal places.)

	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

	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	0.518
VDH	0.062	0.062	0.107	0.083	0.315	0.078

The sub-weights of the different alternatives relative to GOAL for this branch are then obtained by multiplying:

(relative weight for TECHNICAL FEASIBILITY) x (relative weight for CONSTRUCTION) x (relative weight for the alternative)

KBS-3 0.75 x 0.5 x 0.201 = 0.075
MLH 0.75 x 0.5 x 0.201 = 0.075
VLH 0.75 x 0.5 x 0.519 = 0.194
VDH 0.75 x 0.5 x 0.079 = 0.030

To get the total weights for the alternatives, these calculations are then repeated for each branch in the hierarchical structure and all the sub-weights for the alternatives are added together.

Example for KBS-3:

0.075	CONSTRUCTION – TECHNICAL FEASIBILITY – GOAL
0.193	DEPOSITION/SEALING – TECHNICAL FEASIBILITY – GOAL
0.063	HUMAN INTRUSION – GOAL
0.331	TOTAL WEIGHT

REFERENCE

B5-1 Saaty T L
1988
Multicriteria Decision Making – The Analytic Hierarchy Process
(rev. ed.) RWS Publications. Pittsburgh, USA

GUIDELINES FOR EXPERT GROUP FOR "EXPERT JUDGEMENT" OF "TECHNOLOGY"

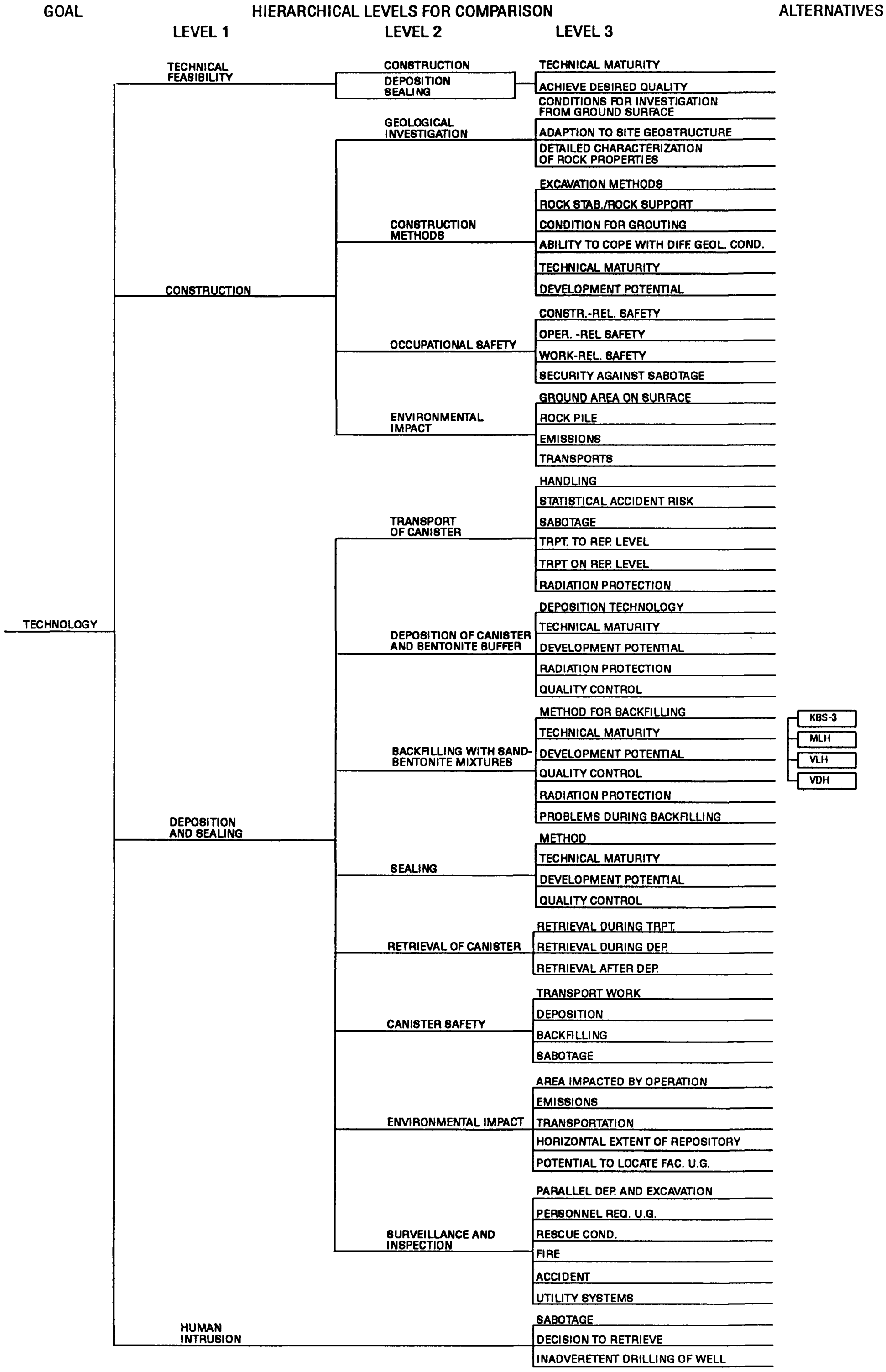


Figure B6-1. *Complete hierarchical structure for interim comparison "Technology".*

TECHNICAL FEASIBILITY

The point of departure is that all four studied systems have previously been deemed to be technically feasible with regard to the excavation work, deposition of the canisters, emplacement of the bentonite buffer around the canisters and backfilling and sealing of the repository. However, the different systems have a varying scale of "proven technology", "partially proven" and "untried in this context".

"Technical feasibility" has been subdivided into (level 2):

- Construction
- Deposition and sealing

The lowest level has been (level 3):

- Technical maturity
- Potential to achieve desired quality in repository

CONSTRUCTION

"Construction" has been subdivided into (level 2):

- Geological investigation
- Construction method
- Safety
- Environmental impact

Geological investigation

"Geological investigation" refers to the accuracy with which important geological data can be determined by means of investigations above and under ground. The heading also refers to the potential for adaptation to the geological model that can be set up on the basis of the investigations.

Level 3 has consisted of

- premises for investigations from the ground surface
- adaptability to geostructures on the site
- detailed characterization of the properties of the rock

Construction methods

Different systems are based on different construction methods in the rock.

- Level 3 has consisted of
- excavation methods
- rock stability/rock support
- conditions for grouting
- ability to cope with difficult geological conditions
- technical maturity
- development potential

Occupational safety

"Occupational safety" refers to several different types of safety questions during construction, but principally those related to the health of the workers.

Level 3 has consisted of

- rockrelated safety issues (cave in)
- operational safety (fire)
- workrelated accidents
- security against external events (sabotage)

Environmental impact

Level 3 has consisted of

- ground area on surface that is affected
- rock pile
- emissions (dust, smoke, exhaust gases, noise)
- transportation

DEPOSITION AND SEALING

"Deposition and sealing" has been subdivided into (level 2)

- transport work
- deposition of canister and bentonite buffer
- backfilling with sandbentonite mixtures
- sealing
- retrievability of canister
- safety regarding canister
- environmental impact
- surveillance and inspection.

Transport of canister

Level 3 has consisted of

- handling
- statistical accident risk
- sabotage
- transport down to repository level
- transport on repository level
- radiation protection

Deposition of canister and bentonite buffer

Level 3 has consisted of

- deposition technology
- technical maturity
- development potential
- radiation protection
- quality control

Backfilling with sandbentonite mixtures

Level 3 has consisted of

- method for backfilling
- technical maturity
- development potential
- quality control
- radiation protection
- problems during backfilling

Sealing

Level 3 has consisted of

- method for sealing
- technical maturity
- development potential
- quality control

Retrievability of canister

Level 3 has consisted of

- retrievability during transport
- retrievability during deposition
- retrievability after deposition

Safety regarding canister

Level 3 has consisted of

- transport work
- deposition
- backfilling
- sabotage

Environmental impact

Level 3 has consisted of

- area impacted during operation
- emissions (dust, smoke, exhaust gases, noise)
- transportation
- horizontal extent of repository
- potential to locate facility sections under ground

Surveillance and inspection

Level 3 has consisted of

- parallel deposition and excavation
- personnel requirement under ground
- rescue conditions (personnel under ground)
- fire
- accident
- utility systems (ventilation, water, electricity)

HUMAN INTRUSION (AFTER SEALING)

Human intrusion has no subdivision on level 2, but on level 3 as follows:

- sabotage for the purpose of damaging the repository or getting at the radioactive materials
- political decision to retrieve the waste
- inadvertent drilling of well into the repository.

RESULTS OF "EXPERT JUDGEMENT" OF DEEP REPOSITORY SYSTEMS WITH RESPECT TO "TECHNOLOGY"

1 HIERARCHICAL STRUCTURE IN INTERIM COMPARISON

The three element levels used in the expert ranking of "Technology" are presented in Appendix 6. This Appendix presents the results only from level 1 and level 2, in addition to the weighed-together final result with respect to the GOAL. The hierarchical structure up to and including level 2 is shown in Figure B7-1.

2 RESULT OF EXPERT RANKING

The final result is presented in Figure B7-2. The 6 experts have been indicated with Roman numerals from I to VI. The mean values of the sub-weights for the different repository systems comprise the arithmetic averages of the experts' different values. The coefficient of variation (CoV) is the standard deviation divided by the mean value.

As is evident from Figure B7-2, KBS-3 is ranked first, followed by MLH and VLH. VDH is ranked last. This order is also found in each expert's rankings, even though the sub-weights in relation to the GOAL vary slightly.

The mathematical treatment of all the values in the pairwise comparison results in sub-weights for the four concepts that are ratio-related to each other. This means that the ratio between the sub-weights for two concepts serves as a measure of their relative value, rather than the absolute difference between them.

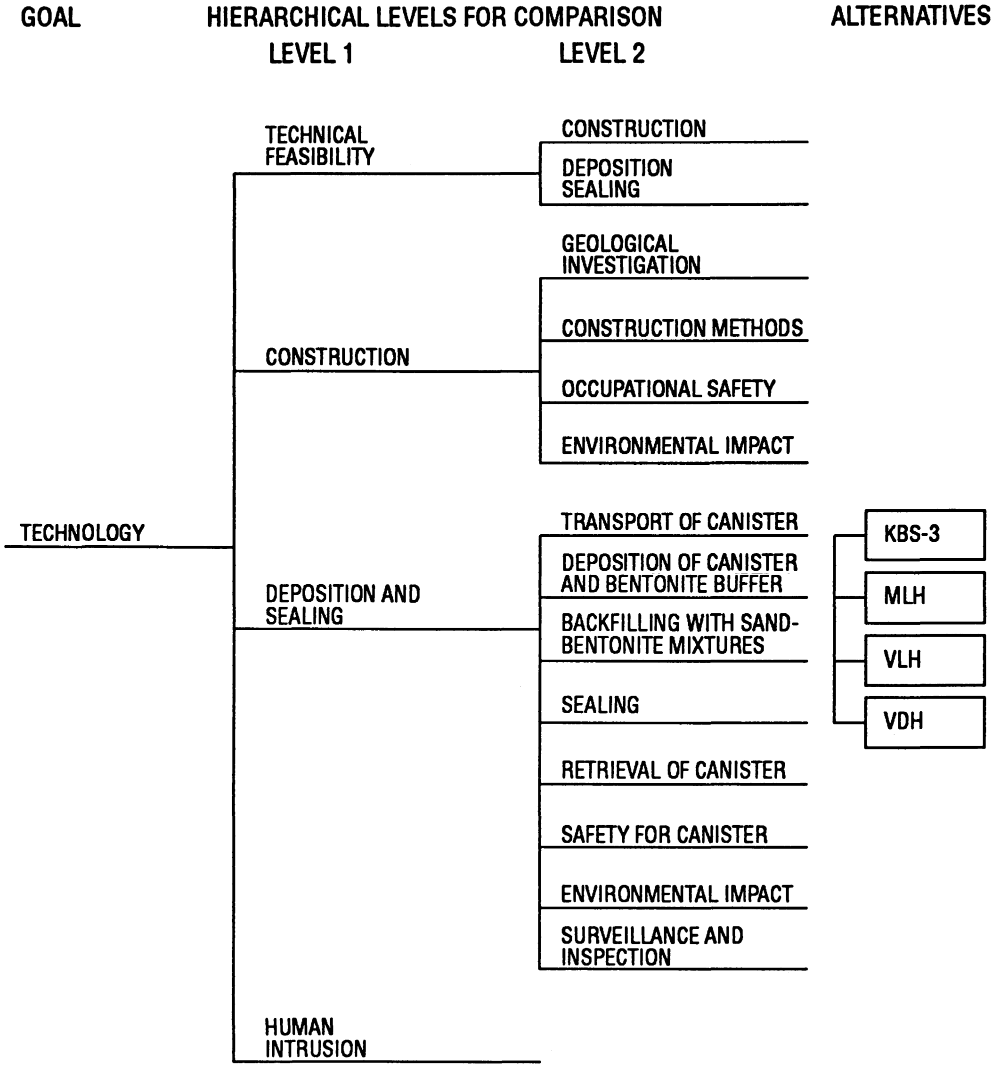
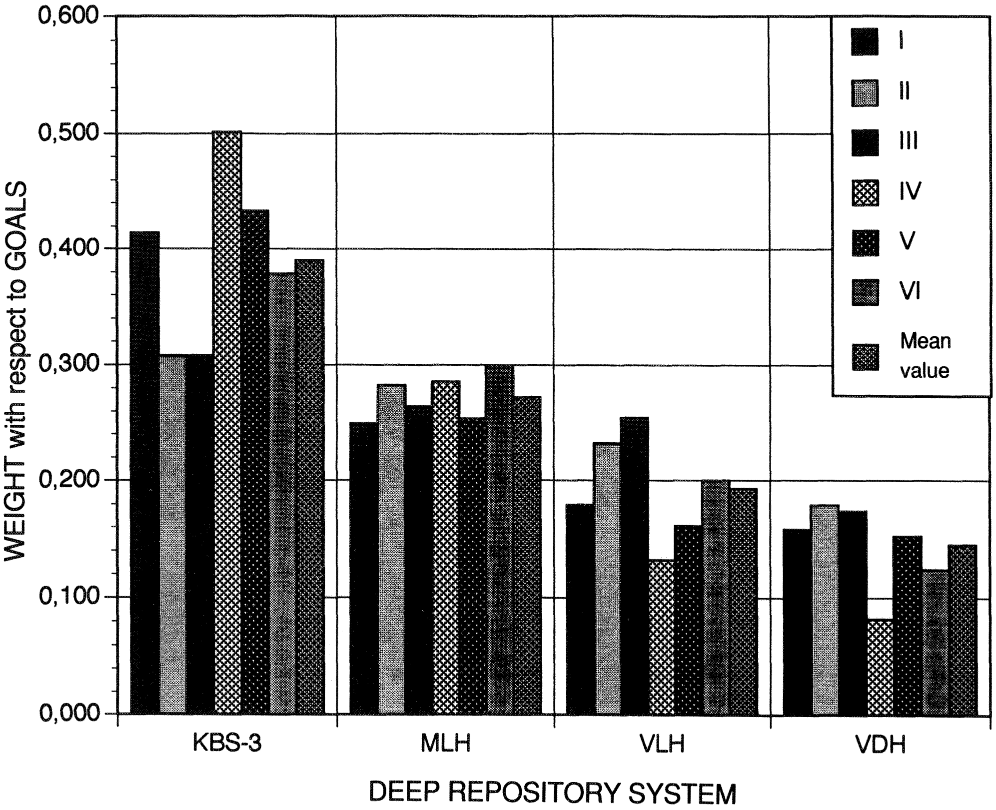


Figure B7-1. *Hierarchical structure for interim comparison "Technology".*

The results in Figure B7-2 therefore indicate that the group believes that KBS-3 is clearly superior to the other systems with respect to "Technology".

If the evaluation results on level 1 (see Figure B7-3) and on level 2 (see Figure B7-4) are also considered, we find that the ranking on these levels is also the same as in the final result.



	I	II	III	IV	V	VI	Mean value	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 B7-2. *Summary of experts' results. The 6 experts are indicated by roman numerals from I to VI.*

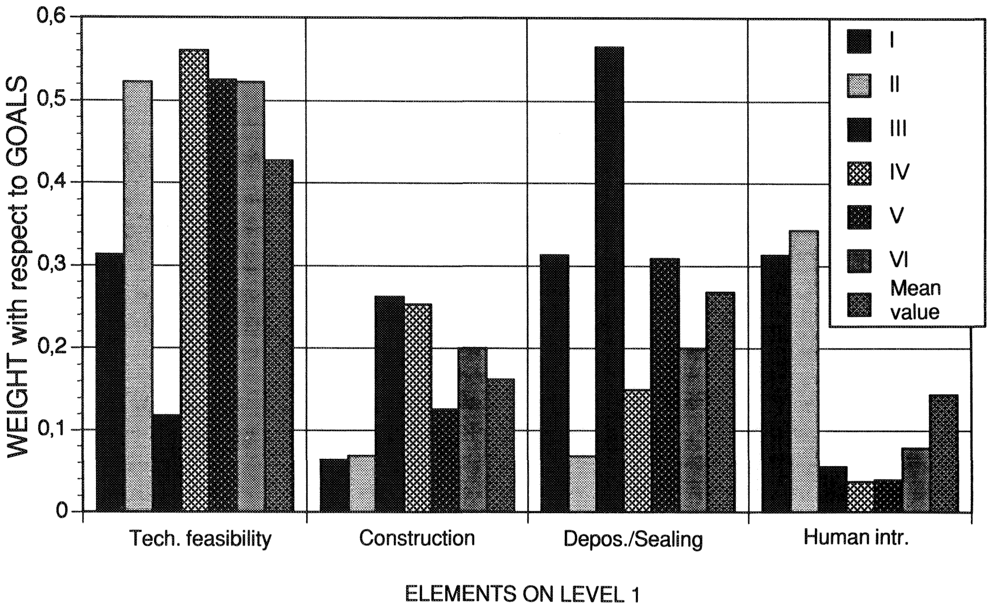
3 SENSITIVITY ANALYSIS

An analysis of the importance of the different elements on level 1 was carried out by counting together without: 1) "Human intrusion" and without 2) "Human intrusion" and "Technical feasibility". For 2) this leaves "Construction" and "Deposition/sealing". The results are shown in Figure B7-5. As can be seen, the same ranking order is retained in both cases.

4 COMMENTS

The experts did their work without having to explain the reasons for their judgements. For this reason, only general conclusions can be drawn from the material.

In a subsequent discussion in the expert group the outcome was analyzed. The group was hereby unanimous in their judgement that KBS-3 represents the most advantageous method, especially with regard to deposition of canisters and bentonite buffer.



	I	II	III	IV	V	VI	Mean value	CoV (%)
Tech.	0,313	0,522	0,118	0,56	0,525	0,522	0,427	41
Construction	0,063	0,068	0,262	0,253	0,126	0,2	0,162	55
Depos./Sealing	0,313	0,068	0,565	0,15	0,309	0,2	0,268	65
Human intr.	0,313	0,343	0,055	0,037	0,039	0,078	0,144	100

Figure B7-3. *Summary of experts' results on "Level I". The 6 experts are indicated by roman numerals from I to VI.*

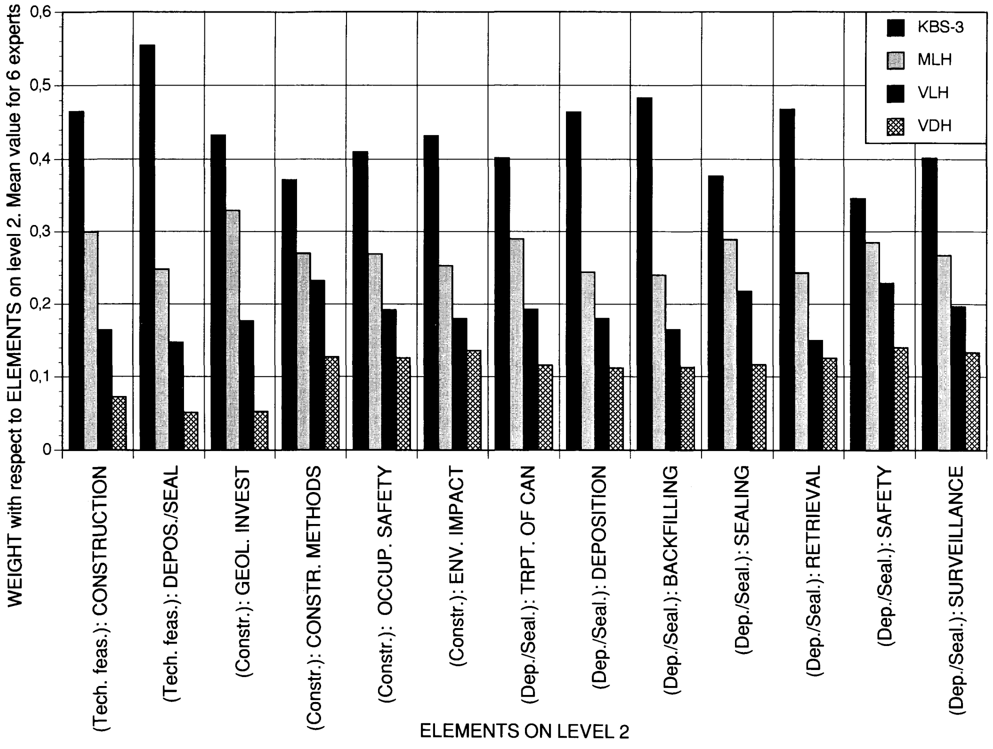


Figure B7-4. *Summary of experts' results on "Level 2". The 6 experts are indicated by roman numerals from I to VI.*

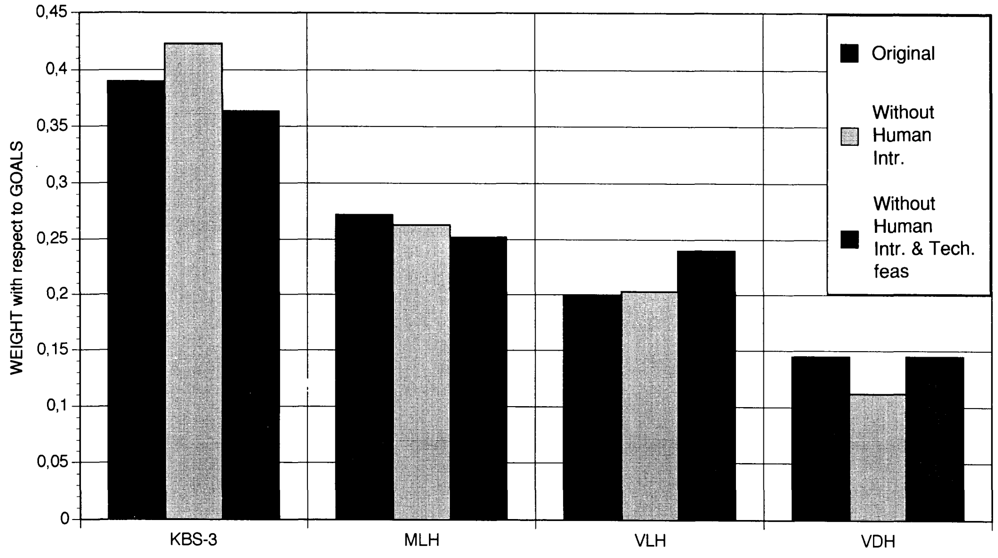


Figure B7-5. *Mean value for the experts of the total result ("Technology") of evaluation with all elements (Original); with "Technical feasibility", "Construction" and "Deposition/Sealing" (Without Human Intr.); and with "Construction" and "Deposition/Sealing" (Without Human Intr. & Tech. feas.).*

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The KBS Annual Report 1980
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The KBS Annual Report 1981
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1991
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Including Summaries of Technical Reports Issued during 1991
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Stockholm, May 1993

Technical Reports
List of SKB Technical Reports 1993

TR 93-01

Stress redistribution and void growth in buttwelded canisters for spent nuclear fuel

B L Josefson[1], L Karlsson[2], H-Å Häggblad[2]

[1] Division of Solid Mechanics, Chalmers University of Technology, Göteborg, Sweden

[2] Division of Computer Aided Design, Luleå University of Technology, Luleå, Sweden

February 1993

TR 93-02

Hydrothermal field test with French candidate clay embedding steel heater in the Stripa mine

R Pusch[1], O Karnland[1], A Lajudie[2], J Lechelle[2], A Bouchet[3]

[1] Clay Technology AB, Sweden

[2] CEA, France

[3] Etude Recherche Materiaux (ERM), France

December 1992

TR 93-03

MX 80 clay exposed to high temperatures and gamma radiation

R Pusch[1], O Karnland[1], A Lajudie[2], A Decarreau[3],

[1] Clay Technology AB, Sweden

[2] CEA, France

[3] Univ. de Poitiers, France

December 1992

TR 93-04

Project on Alternative Systems Study (PASS)

Final report

October 1992

TR 93-05

Studies of natural analogues and geological systems.
Their importance to performance assessment.

Fredrik Brandberg[1], Bertil Grundfelt[1], Lars Olof Höglund[1], Fred Karlsson[2], Kristina Skagius[1], John Smellie[3]

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