

Backfilling and closure of the deep repository

Assessment of backfill concepts

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

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Abstract

This report presents the results from work made in Phase 1 of the joint SKB-Posiva project "Backfilling and Closure of the Deep Repository" aiming at selecting and developing materials and techniques for backfilling and closure of a KBS-3 type repository for spent nuclear fuel. The aim of phase 1, performed as a desk study, was to describe the potential of the suggested backfill concepts in terms of meeting SKB and Posiva requirements, select the most promising ones for further investigation, and to describe methods that can be used for determining the performance of the concepts. The backfilling concepts described in this report differ from each other with respect to backfill materials and installation techniques. The concepts studied are the following:

- Concept A: Compaction of a mixture of bentonite and crushed rock in the tunnel.
- Concept B: Compaction of natural clay with swelling ability in the tunnel.
- Concept C: Compaction of non-swelling soil type in the tunnel combined with application of pre-compacted bentonite blocks at the roof.
- Concept D: Placement of pre-compacted blocks; a number of materials are considered.
- Concept E: Combination of sections consisting of a) crushed rock compacted in the tunnel and b) pre-compacted bentonite blocks. The bentonite sections are installed regularly above every disposal hole.
- Concept F: Combination of sections consisting of a) crushed rock compacted in the tunnel and b) pre-compacted bentonite blocks. The distance between the bentonite sections is adapted to the local geology and hydrology.

The assessment of the concepts is based on performance requirements set for the backfill in the deposition tunnels for providing a stable and safe environment for the bentonite buffer and canister for the repository service time. In order to do this, the backfill should follow certain guidelines, "design criteria" concerning compressibility, hydraulic conductivity, swelling ability, long-term stability, effects on the barriers and technical feasibility. In addition, the risks and need for further investigations were identified for each concept.

The main conclusions from the work done are the following: Concepts A and B, where the material is compacted in the tunnel, are recommended for further studies in phase 2 of the project to investigate if high enough densities can be achieved for the considered materials. Concept C, consisting mainly of non-swelling material has been rejected from further work due to unacceptable uncertainties. Concept D seems to be feasible, although as a new concept it includes various uncertainties linked to materials, manufacturing and installation of the blocks. To be able to settle these uncertainties, Concept D and usage of pre-compacted blocks in tunnel is recommended for further studies in phase 2. Concepts E and F are composed of sections with different types of materials that require separate placement systems. The more complicated backfilling procedure in combination with the question if the high permeability zones in these heterogeneous concepts can comply with the requirements result in a recommendation that no further work should be directed specifically at these concepts in phase 2.

Sammanfattning

I denna rapport presenteras resultaten av fas 1 i projektet ”Återfyllning och Förslutning av Tunnlar och Bergrum” som har som mål att välja samt utveckla material och tekniker för återfyllning och förslutning av slutförvar för använt kärnbränsle av KBS-3 typ. Målet för fas 1, som består av tekniska utredningar, är att beskriva vilka förutsättningar de föreslagna återfyllningskoncepten har för att möta de krav som SKB och Posiva formulerat, välja ut de mest lovande koncepten för vidare studier och beskriva metoder för att verifiera återfyllningskonceptens funktion. De beskrivna återfyllningskoncepten skiljer sig från varandra gällande återfyllningsmaterial och installationsmetod. Följande återfyllningskoncept har studerats:

Koncept A: Blandning av krossat berg och bentonit kompakterad på plats i tunneln.

Koncept B: Svällande lera kompakterad på plats i tunneln.

Koncept C: Icke svällande lera kompakterad på plats samt bentonitblock vid tunneltaket.

Koncept D: Inplacering av block, olika återfyllningsmaterial övervägs.

Koncept E: Kombination of två typer av sektioner a) Krossat berg som packas på plats och b) bentonitblock. Bentonitsektionerna placeras regelbundet över deponeringshålen.

Koncept F: Kombination of två typer av sektioner a) Krossat berg som packas på plats och b) bentonitblock. Bentonitsektionernas placering anpassas till den lokala geologin och hydrogeologin.

Bedömningen av koncepten baseras på funktionskrav som formulerats för att säkerställa en säker miljö för kopparkapseln med använt reaktorbränsle och buffert under djupförvarets drifttid. Dessa krav tillsammans med antagna förhållanden i djupförvaret, salthalt i grundvatten mm, samt ingenjörsmässiga överväganden utgör basen för de konstruktionsförutsättningar som använts för att jämföra koncepten. Konstruktionsförutsättningarna rör krav gällande återfyllningens kompressibilitet, hydrauliska konduktivitet, svälltryck, långtidsstabilitet, negativa effekter på barriärerna i slutförvaret samt bedömning av om installationen är tekniskt genomförbar. Riskerna samt behovet av vidare studier för de individuella koncepten behandlas också i rapporten.

De huvudsakliga rekommendationerna i rapporten kan summeras på följande sätt: Koncept A och B som bygger på packning av återfyllningsmaterial på plats i tunneln ska studeras vidare i nästa fas av projektet för att undersöka om tillräckligt hög densitet kan uppnås för de aktuella materialen. Koncept C, där återfyllningsmaterial till största delen består av icke svällande lera, kommer inte att utredas vidare eftersom det bedöms som osannolikt att det kan uppfylla de ställda kraven. Koncept D har goda möjligheter att uppfylla de ställda kraven, men det är ett nytt återfyllningskoncept och osäkerheter rörande materialval, tillverkning och inplacering av block behöver undersökas i nästa fas. Koncepten E och F består av två olika typer av material som kräver separata återfyllningssystem. Den mera komplicerade återfyllningsproceduren i kombination med frågan om sektionerna med hög permeabilitet kan anses motsvara de ställda kraven resulterar i en rekommendation att dessa koncept inte direkt ska undersökas vidare i fas 2.

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1 Introduction

SKB in Sweden and Posiva in Finland are developing and implementing similar concepts for the disposal of spent nuclear fuel. The KBS-3 deep repository will be backfilled to comply with requirements specified by SKB and Posiva and the respective national authorities. The requirements set on the backfilled tunnels, for the service time of the repository, are to prevent the tunnels from becoming preferential flow paths for water, keep the buffer in place in the deposition holes, and not to have any harmful effects on the barriers in the repository. A joint project with the purpose of selecting and developing material and technique for the backfilling and closure of deep repositories has been launched.

The overall objective of the project is to develop backfill concepts and techniques for backfilling and closure of the deep repository. This will comprise backfilling of access routes (shafts, ramp), central tunnels, deposition tunnels and other excavations. The work presented in this report is, however, mainly focused on the backfilling of the deposition tunnels.

SKB and Posiva have previously conducted research on suitable backfill materials and techniques for deposition tunnels. This work comprises both laboratory test and full-scale tests of tunnel backfilling. The reference backfill material has so far been a mixture of crushed rock and 15% bentonite expressed in weight-percent. In laboratory and full-scale tests mixtures with 0%, 10%, 20% and 30% bentonite have been investigated. The backfilling technique developed for the full-scale tests has been in-situ compaction of inclined layers. The results from the work so far indicate that, for the ground water conditions prevailing in the Äspö HRL where the salt content in the ground water is about 1%, the long term safety requirements could probably be met with the developed technique using 30% bentonite in the mixture.

The sites under study in both Finland and Sweden are in coastal regime and high salinities of the groundwater are foreseen at depth. In combination with results from recent research, mainly concerning the deterioration of the properties of low density bentonite under the influence of salt in the saturating water, this emphasizes the need for further development of backfilling concepts. There is also a need to develop backfill concepts for other excavations: caverns, transport tunnels, shafts and ramps and methods for closure of the repository. The finally selected techniques will also have to be developed for effective production backfilling.

The project “*Backfilling and Closure of the Deep Repository*” is divided into four major phases:

- Phase 1: Desk studies to identify backfill concepts and select a few promising ones for further studies.
- Phase 2: Preliminary experiments and more profound analyses to study the preferred concepts and for selection of a few main alternatives.
- Phase 3: Pilot tests with prototype equipment to verify the engineering feasibility of the main alternatives and for qualifying methods for showing compliance.
- Phase 4: Large field-tests – overall verification and “dress rehearsal” of non-nuclear operation.

The main objectives of the first phase of the project are to:

- Describe the potential of the suggested concepts in terms of meeting the requirements.
- Choose the most promising concepts for further investigation.
- Describe the methods that will be used for determining the performance of the concepts.

This report is based on the work performed in phase 1 and comprises description and assessment of the backfill concepts. It also comprises a recommendation on which concepts should be chosen for further investigation. The scope of work necessary to further investigate the concepts is also stated.

Most of the concepts, all except one, described in this report only concerns the back-filling of the tunnels and does not address the sealing of a possible axially hydraulic conductive damaged zone in the rock. The nature and hydraulic properties of this zone is being investigated in other SKB and Posiva projects /SKB, 2001; Posiva 2003/. If it appears that the damaged zone could influence the long term safety, it may be necessary to seal it. An engineering solution, based for example on the principle suggested in Concept F could be one way to do this.

2 Design criteria

In this chapter, the SKB and Posiva performance requirements on the backfill and concerns raised by reviewing authorities are listed. The requirements are interpreted into design criteria that are used as tools for assessing and comparing the investigated concepts. The design criteria are listed and described. Methods for showing compliance with the design criteria are also suggested. The design criteria should not be considered as final quantifications of the requirements but as guidelines that will be continuously updated as the knowledge increases.

In addition to the design criteria that are based on SKB's and Posiva's performance requirements, the technical feasibility of the installation is also formulated as a design criterion.

2.1 Performance requirements for the backfill

2.1.1 Concerns by external reviewers

The Swedish authority SKI did express several concerns and advices in reviewing the SKB RD&D Program 2001:

- Choice of material etc for backfill should be made in good time before the application license to construct the deep repository is reviewed by the authorities.
- The Äspö HRL Backfill and Plug Tests are not sufficient, additional materials need to be tested.
- Sealing function required for a range of future salinities in the groundwater.
- It is necessary that the backfill is incompressible enough to achieve the function of the buffer.

STUK in Finland treats /STUK, 2001/ the backfill as a part of the engineered barrier system – “the backfilling materials and sealing structures, which limit transport of radioactive substances through excavated rooms”. In the same document STUK also states “Targets for the long-term performance of each barrier shall be determined based on best available experimental knowledge and expert judgment. The performance of a barrier may diverge from the respective target value due to rare incidental deviations such as manufacturing or installation failures of engineered barriers, random variations in the characteristics of the natural barriers or erroneous determination of the characteristics. However, the performance targets for the system of barriers as a whole shall be set so that the safety requirements are met withstanding the deviations referred to above.”

2.1.2 Concerns by the implementers SKB and Posiva

This section introduces the performance requirements set on the backfill by SKB and Posiva. They will be further interpreted and discussed in section 2.2.

SKB

The backfilled tunnels are a part of the bedrock barrier that is described in the following way in the general description of the KBS-3 system: “The rock that surrounds the final repository has been chosen so that the flow of ground water in it is very low. A strong retardation of most radioactive substances also takes place in the rock through chemical processes between the minerals and the radioactive substances. In this manner, a very large portion of the radioactivity will have time to decay during its transport in the rock. Hence the tunnels shall be backfilled so that the function of the bedrock is not compromised.”

Hence four requirements interpreted from /SKB, 2002/ on the backfill can be stated:

1. Compressibility

In order to maintain the density of the buffer the backfill shall have a compressibility that is low enough to minimize the upward expansion of the buffer.

2. Hydraulic conductivity

In order to prevent the deposition tunnels from being conductive pathways that influence the water movement in the repository the backfill shall, over the entire length and cross-section of the tunnel, have a hydraulic conductivity in the same order of magnitude as that of the surrounding rock, or so low that the water transport is dominated by diffusion.

3. No harmful effects on other barriers

The backfilled tunnels shall not have any negative influence on the barriers in the repository.

4. Long-time stability

The backfill shall be stable in a long-term perspective and its functions be maintained under the expected repository conditions.

Posiva

With respect to backfill, Posiva states that the backfill shall /Posiva, 2000/:

- A. Keep the buffer and canister in place in the deposition hole.
- B. Prevent the tunnels from becoming major conductors of groundwater and transport pathways of radionuclides.
- C. Shall not have any harmful chemical interaction with other barriers.
- D. Contribute to the stability of the tunnels.

2.2 Design criteria and methods for showing compliance

This chapter introduces the design criteria defined for the backfilling concepts. These design criteria are used as tools for assessing and comparing the investigated concepts. However, they should not be considered as a final quantification of the requirements, since the work to be performed within this project will result in more detailed knowledge that would be used for refining and improving the design criteria. The design criteria presented in this chapter are based on the SKB and Posiva requirements listed in Chapter 2.1, assumptions concerning site characteristics and engineering considerations.

The design criteria stated here is valid for deposition tunnels. It is probable that SKB and Posiva requirements may result in different design criteria in other parts of the repository depending on site characteristics and repository layout etc.

Methods for determining if the concepts can fulfil the design criteria and thereby comply with the SKB/Posiva requirements are also suggested in this chapter.

The design criteria concerning compressibility, hydraulic conductivity, swelling pressure, long-term stability and harmful effects on the other barriers, specified below will be used for choosing promising materials for different concepts. In addition, the technical feasibility will also be handled as a design criterion.

2.2.1 Compressibility

The compressibility of the backfill should be low enough to ensure that the swelling of the buffer does not influence the buffer density so that the function is compromised. This design criterion originates from the SKB performance requirement 1 and Posiva performance requirement A (see Chapter 2.1).

Method for showing compliance

Laboratory tests that determine the mechanical properties of the backfill material in the concept will be made. Calculations that determine what density is required in order not to influence the density of the buffer between the canister and the rock will be made. The calculation will show if it is possible to use the respective material, and if so, define a minimum density that has to be achieved when backfilling the tunnels.

The dislocation of the buffer/backfill contact and the resulting decrease in buffer density for a tunnel backfilled with Friedton clay at a density obtained in field tests was calculated by /Johannesson and Börgesson, 2002/. The same type of calculation will be used for determining if other backfill material can be used, and if so, define the minimum density.

2.2.2 Hydraulic conductivity and swelling pressure

A hydraulic conductivity of $1E-10$ m/s and a swelling pressure of > 100 kPa at a ground water salt content of 35 g/l TDS is used as a guideline for this project. This design criterion originates from the SKB performance requirement 2 and Posiva performance requirement B (see Chapter 2.1).

Method for showing compliance

The hydraulic conductivity of proposed materials should be measured in a Proctor cylinder adapted for measuring hydraulic conductivity or similar. This method is for example described by /Johannesson et al, 1999/. It is also possible to use other suitable methods for measurement of hydraulic conductivity. The hydraulic conductivity will be measured on samples with densities that are in the same range as can be achieved in the field. The salinity of the water used for saturation and percolation will be varied to investigate how this affects the different proposed backfill materials. If the material is intended to be used as a swelling component in a backfill concept, a test that confirms that the net swelling pressure is at least 100 kPa will be made. These types of tests are also described by /Johannesson et al, 1999/.

The scale-effect should be taken into account when analysing the test results and therefore the laboratory values should be verified through larger scale laboratory and field tests.

The laboratory tests will show if the material can be used as backfill material, and if so, what minimum density has to be achieved when backfilling the tunnels.

2.2.3 Long-term stability

The long-time stability of the materials will be investigated, mainly within the SR-Can /SKB, 2003/. This design criterion originates from the SKB performance requirement 4 and Posiva performance requirements C and D (see Chapter 2.1).

2.2.4 No harmful effects on the other barriers

An investigation of whether there are any harmful effects on rock, buffer or canister will be made, mainly within the SR-Can /SKB, 2003/. This design criterion originates from the SKB performance requirement 3 and Posiva performance requirement C (see Chapter 2.1).

2.2.5 Technical feasibility

The matter of technical feasibility does not originate directly from the Posiva and SKB performance requirements. However, to fulfil the performance requirements and design basis in practice, the concept has to be technically feasible.

In addition to the performance requirements for the backfill placed in the tunnels, there are other requirements for the backfilling concept like:

- Simple problem-free applicability.
- Sufficient backfilling rate.
- Cost optimisation.

To achieve good feasibility it is important to have a backfilling rate that is high enough to ensure that the vertical expansion of the buffer is limited during the backfilling operation. The relationship between the backfilling rate and the maximal allowable water inflow into the tunnel for different backfilling concepts during backfilling will also have to be defined. If the inflow of water is too high, practical problems such as too quick swelling leading to loss of density, adhesion of the backfill material to compaction equipment etc. will occur.

If no acceptable engineering solution for handling the water inflow during operation can be developed, piping can probably not be avoided in the installation phase, irrespective what type of backfill material is used. Even if the water inflow can be decreased to low levels, in the order of 10 l/min per deposition tunnel, a point leakage of 1 l/min with a pressure build up rate that can be expected at the depth of the repository will most probably result in piping and surface erosion (Figure 2-1). As the backfilling front passes a point leakage the pressure starts to rise at the contact between the rock and the backfill. For the case of in-situ compaction, this means that for the time of the compaction of one layer, say 2 hours, about 30 cm backfill without support shall withstand the increase in water pressure. This quickly results in a high water pressure gradient that probably results in piping between the point leakage and the open tunnel volume. When the next layer is applied the water has already created piping through the first layer and the pressure will start to rise in the contact between the two layers and the rock. This probably leads to piping through the next layer and so on. The backfill therefore needs to have sufficient swelling ability so that channels can be healed when the flow along the tunnel is finally cut off by a plug. If the plug does not act as an effective seal, water will continue to flow in the piping channels.

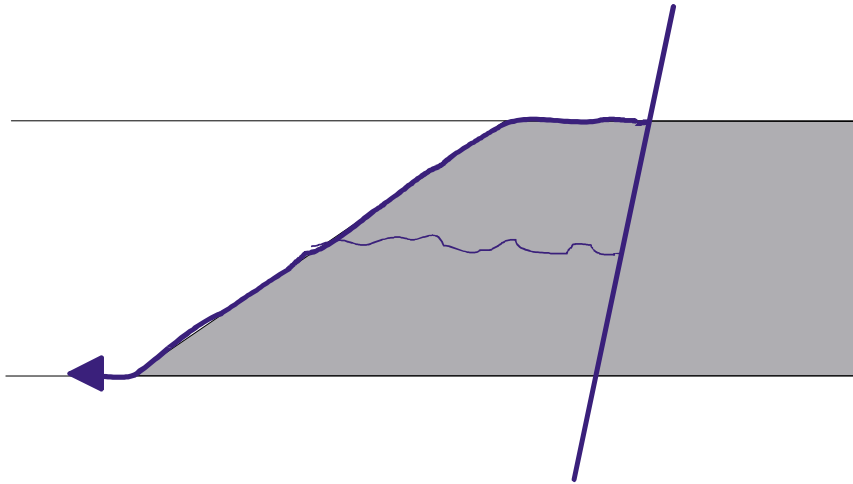


Figure 2-1. Schematic drawing of the piping that will probably occur during backfilling. The straight line represents a channel in the backfill, initiated by pressurized water in a rock fracture.

SKB has stated that about 6 m tunnel per day should be backfilled. This is based on the assumed deposition rate of one canister per day and about six metres distance between the centre of the deposition holes. This is not an absolute requirement since it will be possible to backfill two tunnels simultaneously. Other factors setting the rate, i.e. change in water ratio, swelling of buffer, etc, call for a high backfilling rate but no criteria have yet been defined.

Posiva's requirement for the backfilling rate is 10 m/week. This backfilling rate is based on a deposition rate of 40 canisters per year. Higher backfilling rate should be favourable when considering the technical feasibility.

2.3 Assessment methodology

The assessment methodology used is presented as a flow chart in Figure 2-2. It is applied to each concept in this chapter and summarized in Chapter 10.

The purpose of the assessment is to, based on the present level of knowledge, evaluate the probability that the concept can meet the requirements stated in Chapter 2.2.

The general idea is to assess the concepts stepwise, considering a number of specified aspects of the concept. If the outcome from one assessment step is that there is no possibility or very low probability that the concept can function according to this aspect, the concept will be disqualified and the recommendation will be that no further work is directed at the particular concept.

In the first step of the assessment uncertainties concerning installation, cost etc are not considered. Technical feasibility is hence disregarded in this first examination.

In the second step it is assessed if it is technically possible to emplace the material in the tunnel with high enough density to fulfil the requirements as interpreted in the design criteria concerning compressibility, hydraulic conductivity, swelling pressure, long-term stability and possible harmful effects on the other barriers. It is evaluated if the requirements can be fulfilled in practice, as described in the design criterion concerning technical feasibility.

In step 3 the amount of R&D work needed to a) gain enough knowledge to determine if the concept meets the requirements and b) to develop adequate filling and compaction techniques, is listed.

In step 4 the cost of the concept is estimated.

In step 5 the risk for failure is assessed. This risk assessment is divided into two parts;

1. The uncertainties with the concept in terms of meeting the design criteria as they are formulated today are highlighted and assessed
2. The risk of failure during the development due to changes in the requirements or changes in the interpretation of the requirements. How robust the concepts are, how sensitive they are to changes in salt content in the ground water etc. will be addressed

Finally the assessment is summarized and a recommendation on if the concept should be further investigated and developed or not is made. The assessment is summarized in Chapter 9.

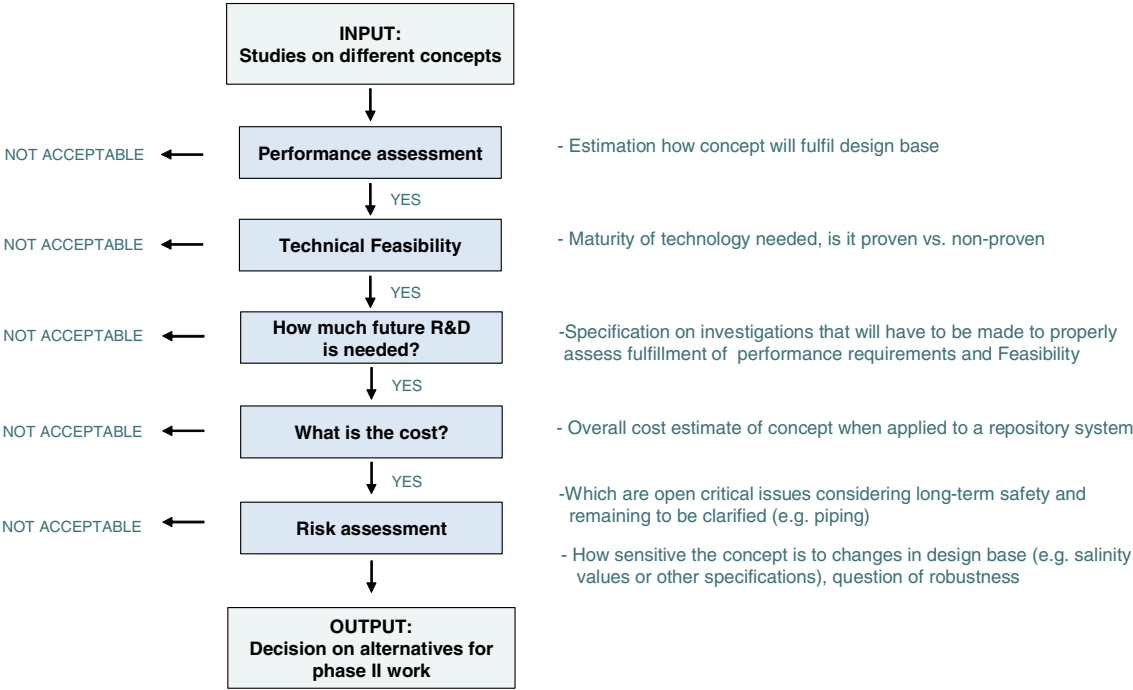


Figure 2-2. The structure of the assessment methodology.

3 Concept A: Compaction of bentonite and crushed rock mixture in the tunnel

Concept A has so far been the reference backfilling concept. It has been developed by SKB through a series of laboratory and field tests. In the reference concept the backfill material consists of 15% bentonite and 85% crushed rock (by dry weight). As the influence of the salt content of the saturating water on the properties of the backfill was noticed the bentonite content was raised to 30% for the full-scale tests conducted in the Äspö HRL.

The *Field Test of Tunnel Backfilling*, reported by /Gunnarsson et al, 1996/, was conducted in a TBM-tunnel in the Äspö HRL in 1996. Horizontal layers were compacted to a height of about 1.55 m from the floor. The rest of the tunnel was backfilled with inclined 20 cm thick layers with about 35 degrees angle to the floor. Mixtures with 10%, 20% and 30% bentonite content (by dry weight) were tested. One important conclusion from the test was that the horizontal layers were sensitive to water inflow, and that it was more favourable to backfill the entire cross-section with inclined layers. The densities achieved in the field in combination with results from laboratory tests reported by /Börgesson et al, 1996/ indicated that a bentonite content of 30% was necessary to fulfil the requirements of the backfill when the salt content of the ground water exceeded about 1%.

The *Backfill and Plug Test* was installed in a drill and blast tunnel in the Äspö HRL during 1999. In the test a 28 m long tunnel section was backfilled and instrumented. Half of the length was backfilled with a mixture of 30% bentonite and 70% crushed rock, and the other half was backfilled with crushed rock and bentonite blocks placed at the roof. The installation of the test is described by /Gunnarsson et al, 2001a/. Similar material and technique was later used for the installation of the Prototype Repository.

The main conclusions regarding compaction of bentonite/crushed rock mixtures in the tunnel are that inclined compaction over the entire tunnel cross-section seems to be a suitable backfilling technique, and that out of the tested materials, a mixture of 30% bentonite and 70% crushed rock is suitable. Preliminary results from the measurements made during installation of the Backfill and Plug Test and the Prototype Repository indicate that the requirements on the backfill can be met for ground water salt contents up to about 1% when backfilling is made with this technique and material /Gunnarsson and Börgesson, 2002/. A compilation of materials used in earlier tests is made in Table 3-1.

Table 3-1. Compilation of backfill materials used in earlier tests.

TEST	Type of ballast	Max grain size	Bentonite	Amount	Layer	Reference	Note
Prototype Repository	Crushed TBM-muck	20 mm	Milos converted Na-bentonite	30%	Inclined	/Gunnarsson, 2002/	
Pre test for Prototype Repository	Crushed TBM-muck	5 mm	Milos converted Na-bentonite	30%	Inclined	/Gunnarsson et al, 2001b/	Handling of muck was difficult
Backfill and Plug Test	Crushed rock + added fine fractions	20 mm	Na-bentonite (MX-80)	0/100% 30/70%	Inclined	/Gunnarsson et al, 2001a/	
Field test of tunnel backfilling	TBM-muck	20 mm	Na-bentonite (MX-80)	0/100% 10/90% 20/80% 30/70%	Horizontal Inclined	/Gunnarsson et al, 1996/	TBM-tunnel

3.1 Description of concept A

3.1.1 Material and layout

The layout of concept A is presented in Figure 3-1. The entire cross-section of the tunnel is filled with a mixture of bentonite and crushed rock with a maximum grain size of 20 mm. This type of material has been tested in laboratory and field compaction tests. So far, the ballast component has been rock from the tunnel crushed to a grain size distribution that facilitates compaction and the bentonite has been MX-80 Na-bentonite from Wyoming (USA) or Milos Na-converted Ca-bentonite from Greece.

3.1.2 Processing and mixing

The material is mixed and adjusted to the optimal water ratio above ground. In the field tests described by /Gunnarsson et al, 2001a; Gunnarsson, 2002/, the mixing has been made in a transportable concrete paddle mixer. In order to achieve good enough homogeneity in the production of backfill material for the deep repository an Eirich mixer should be used. The crushing equipment has to be specially designed to crush the material into the desired grain size distribution.

3.1.3 Placement

The material is applied and compacted into inclined layers in the tunnel according to the principle shown in Figure 3-2. In the full-scale tests made so far, the compacted layer thickness has been 20 cm. The letters a–f in Figure 3-2 indicate the different steps of the backfilling: a–b) moving the material into the tunnel by pushing it in place, c) compacting the material at the roof, d–f) compacting the rest of the layer. The development of the backfilling technique is described by /Gunnarsson and Börgesson, 2002/.

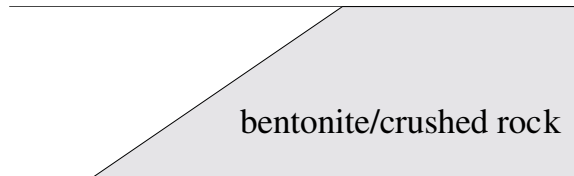


Figure 3-1. The layout of concept A.

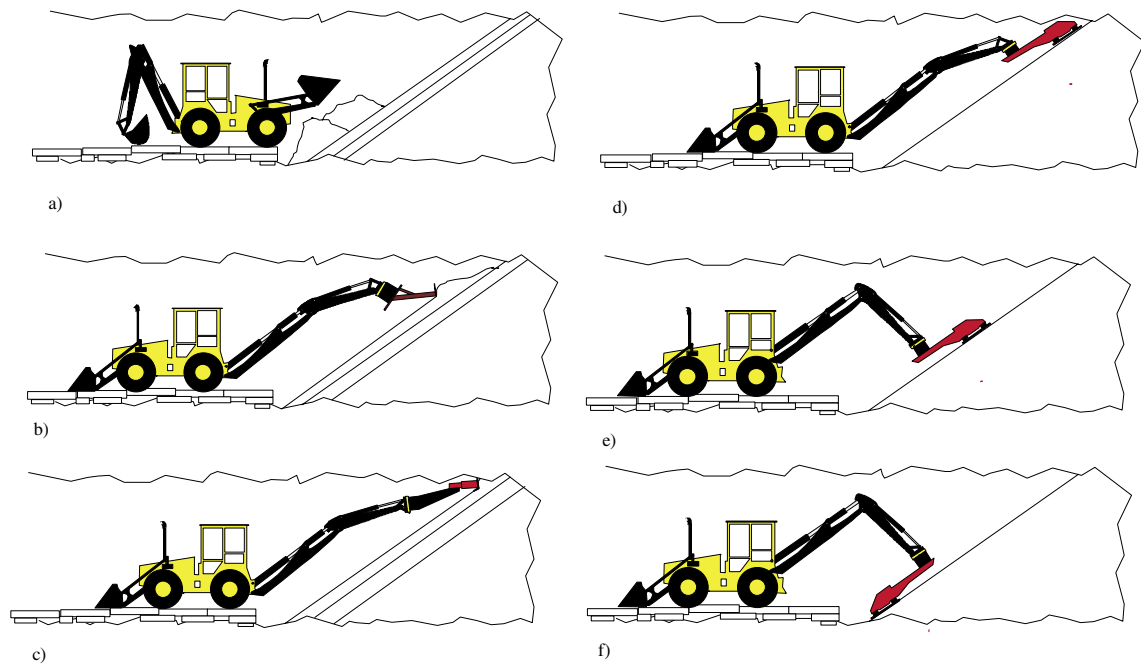


Figure 3-2. Compaction of inclined layers of backfill material in a tunnel.

3.1.4 Logistics

The backfill material is prepared above ground in a production plant and transported to the repository level by truck or by skip. The material is intermediately stored in a “box feeder” and then transferred to a transport unit that carries it to the deposition tunnel. The procedure for conveying the material to the tunnel front has not been developed, but it can, for example, be done by means of a flexible conveyor belt attached to the transport truck that moves the material into the tunnel and delivers it to the compaction equipment. The logistics are described in /SKB, 2002/.

3.1.5 Quality assurance

The grain size distribution of the ballast is tested after crushing. The clay component is tested in the same way as the clay for the buffer.

After the mixing the water ratio is determined and compared to limit values. The mixed material is sampled to determine the homogeneity with respect to the bentonite content.

During placement, the density is determined by measuring the rebound during compaction. It is calibrated against density by the use of nuclear density meters and by mass/volume determination. Samples are taken from the compacted material to determine the final water ratio and amounts of pollutants.

3.1.6 Application of the concept for other excavations

If the material can be compacted to high enough densities to fulfil the requirements in the deposition tunnels, it should not be a problem to adapt the concept to the backfilling of other excavations. The mechanical demands on the backfill are not valid for other excavations and it may be that the hydraulic conductivity can be allowed to be higher at some distance from these tunnels.

Caverns

In general, a larger carrier can be used for larger openings, which also makes it possible to handle a larger and more powerful compactor compared to the situation in disposal tunnels. Tunnels higher than 10 m are preferably backfilled in two or more steps.

Transport tunnels

If the transport tunnels are of about the same size as the deposition tunnels, the same backfilling technique and material can be used, but poorer properties of the fill can probably be accepted.

Ramp

The same recommendations are valid as for the transport tunnels but there is less need for effective sealing. Problems with inflowing water will probably be greater in the ramp since it will most probably intersect larger fracture zones. This can probably be solved with a drainage system for wet sections of the tunnels and with temporary plugs.

Shaft

Other types of compaction technique will have to be used in shafts. Here, high compaction energy can be applied and higher density obtained than in the tunnels. Possible compaction techniques involve: stamping, use of vibrating plates, falling weight and self-compaction by gravity. On the other hand, the problems with water inflow can be greater for shafts than for the deposition tunnels. The water coming from below can probably be handled in the same way as for the ramp with plugs and drainage sections. The water coming from above will have to be collected to avoid softening of the backfill surface. A special device for doing this will have to be designed. A system for bringing material down in the shaft and past the compaction equipment has to be developed.

3.2 Assessment of concept A

3.2.1 Fulfilment of performance requirements

The requirements have been interpreted to four design criteria (see Chapter 2). In this section the possibility to fulfil these design criteria is assessed.

Compressibility

Laboratory tests for determining the mechanical properties of crushed rock mixed with 10%, 20% and 30% MX-80 bentonite has been made by /Börgesson et al, 1996/. According to these tests, a compression modulus of 10 MPa was concluded to be sufficient for this type of material. The results are summarized in Table 3-2. The tests were made with fresh water and water with salt content of 1.2% (Äspö water). There was no indication that even higher salt content in the saturation water would have a negative influence on the mechanical properties of the material. In general, the conceptual understanding of the mechanical properties of the material is that the skeleton of the soil, or rather the crushed rock, takes the mechanical load and that the mechanical properties of the material hence should be independent of the salt content of the water which only affects the properties of the clay fraction of the material. This still needs to be verified in laboratory tests for higher salt contents of the saturating water.

Table 3-2. Summary of the compression tests, referring to /Börgesson et al, 1996/.

Material	Proctor (%)	Water	ρ_d (g/cm ³)	e	M (MPa)	p_i (kPa)
crushed TBM	88	distilled	2.026	0.343	26.5	100
crushed TBM	92	distilled	2.109	0.29	25.1	100
crushed TBM	91	distilled	2.095	0.329	41.4	100
crushed TBM	98	Äspö*	2.247	0.219	91.5	90
crushed TBM	90	Äspö	2.068	0.325	29.2	50
10/90	89	distilled	1.907	0.423	24.9	100
10/90	93	distilled	2.006	0.286	46.8	200
10/90	94	Äspö	2.016	0.347	68.5	175
20/80	85	distilled	1.736	0.579	17.9	150
20/80	93	distilled	1.909	0.435	40.4	400
20/80	93	Äspö	1.914	0.432	38.9	300
30/70	88	distilled	1.707	0.619	16.4	300
30/70	93	distilled	1.813	0.516	26.5	600
30/70	94	Äspö	1.826	0.492	55.3	500
30/70	88	Äspö	1.721	0.604	12.4	200

*) Total salinity of the pore water 1.2%.

Hydraulic conductivity and swelling pressure

As shown in Figure 3-3, a hydraulic conductivity lower than $1\text{E-}10$ m/s can be fulfilled in laboratory tests for a salt content of 1.2% in the saturating water, if the dry density is equal or higher than 1.7 g/cm^3 . So far, no tests have been made for salt contents higher than 1.2%. The hydraulic conductivity can be assumed to be a function of the density of the bentonite in the pore system of the material, assuming that there is enough bentonite to fill the pore system and that it is homogeneously distributed. The bentonite density can be calculated as the weight of the bentonite divided by the volume of the pore system.

The hydraulic conductivity of pure bentonite at different salt contents of the saturating water has been determined by /Börgesson et al, 1995/. By applying the results, the “*effective clay dry density*” has been calculated as a function of the theoretical hydraulic conductivity of for the mixture (see Figure 3-3). This ideal hydraulic conductivity differs significantly from the hydraulic conductivity measured for the actual 30/70-mixture. The difference is probably caused by non-homogeneous distribution of the bentonite in the pore system, as suggested by /Börgesson et al, 2003/. The anticipated theoretical increase in the hydraulic conductivity when the salt content was raised from 0 to 1.2% is, as shown in Figure 3-3, not very high, but it still results in an increase of more than one order of magnitude. If this is extrapolated to an increase in ground water salinity to 3.5%, the increase in the actual hydraulic conductivity of the material would be very strong. Since the reason for the difference between the theoretical and the measured hydraulic conductivity may be due to inhomogeneous distribution of the bentonite in the mixture, it should be tested whether the mixing technique can be improved and if this affects the hydraulic conductivity.

Another subject that requires further study is the effect of the grain size distribution on the geotechnical properties of the material, since only mixtures with Fuller type of grain size distribution curve have been tested. The grain size distribution affects the possibility to reach a high density, and thereby, the hydraulic conductivity of the material. If the crushed rock grains are uniform in size and shape there will be large voids between the grains. The clay then remains uncompacted in the “pockets”, which leads to low clay density and high sensitivity to salinity.

Since it seems to be theoretically possible to decrease the hydraulic conductivity to acceptable levels also for higher salt contents than 1.2%, it is recommended that this concept should be investigated further in the next phase.

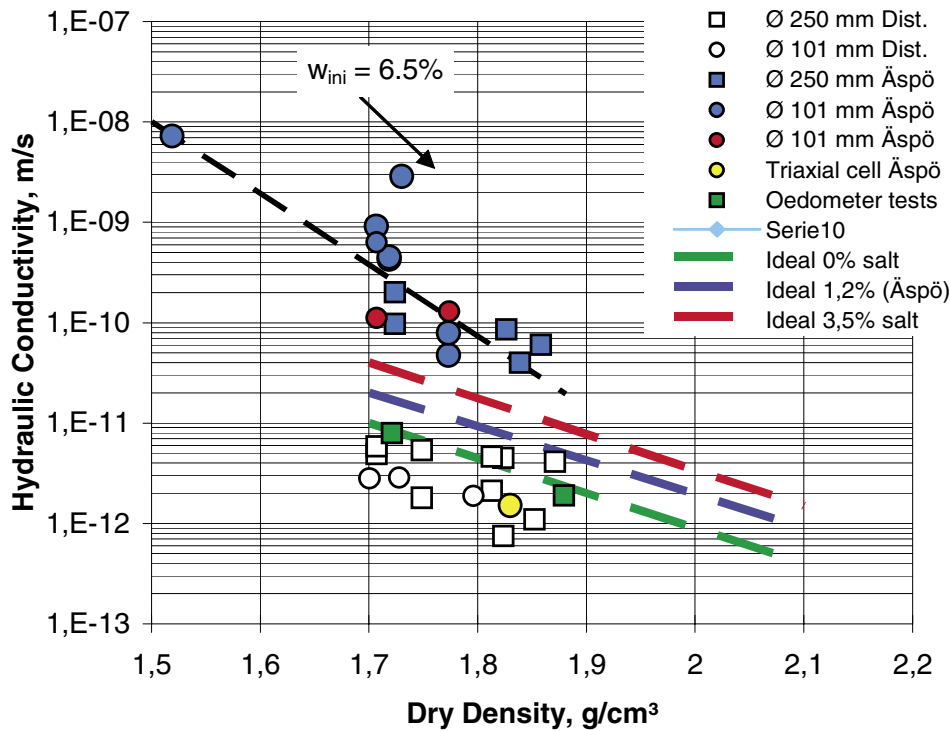


Figure 3-3. Hydraulic conductivity determined on 30/70 mixture. The “ideal” hydraulic conductivity is based on measurements by /Börgeesson et al, 1995/. The rest of the data emanate from /Johannesson et al, 1999/.

Table 3-3. Summary of the swelling pressure tests performed with Äspö water.

Test No.	Clay cont (%)	w_{ini} (%)	Final properties			ρ_d (t/m ³)	e	Sr (%)	Swelling pressure (kPa)
			Proctor (%)	w (%)					
1	30	6.3	89	21	1.73	0.59	97	220	
2	30	13	88	21	1.71	0.61	96	244	
3	30	13	78	27	1.52	0.81	93	68	
4	20	8	79	23	1.62	0.69	91	21	

Table 3-3 presents a summary on swelling pressure tests performed with “Äspö water” (1.2% salt, 50:50 NaCl and CaCl₂). The results show that the desired swelling pressure, 100 kPa, was reached for the tested densities saturated with water with 1.2% salinity.

Long-term stability

The components used in the mixture are considered stable under the conditions prevailing in the deep repository. If the backfill consists of much coarser material than the buffer clay, “contact” erosion can occur at the interface of these two different types of materials. The fine buffer clay can be transported into the pore system of the backfill along with the flow of groundwater in this interface zone. Most of the work directed at the long-time function of the backfill will be addressed in the SR-CAN /SKB, 2003/.

No harmful effects on other barriers

The components used in the mixture are not considered to have any direct harmful effect on the barriers in the deep repository even though feldspars in the backfill giving off potassium will have an effect on the chemical stability of the buffer in a long-term perspective. No specific work will be directed at this issue within this project. However, the interaction between bentonite/rock and the other barriers will be studied in other SKB and Posiva projects.

3.2.2 Technical feasibility

In the full-scale tests performed at the Äspö HRL it has been shown that it is possible to mix bentonite and crushed rock in a large scale and to backfill blasted and drilled tunnels and, at least in drilled tunnels, to achieve a high density in all parts of the tunnel. What remains to be determined is if the material and the placement technique can be improved so that the requirements are fulfilled also for salt contents of 3.5% in the groundwater. To do this, the mixing procedure has to be changed so that a better homogeneity can be achieved.

In addition, it will be studied whether a high density of the clay phase can be achieved by modifying the grain size distribution of the crushed rock.

The backfilling equipment has to be further developed to be able to increase both the density of the backfill and the backfilling rate in the tunnels.

One problem with the feasibility of this concept is that if the water inflow to the tunnel is not very low, piping will occur during installation. The 30/70 mixture must be able to seal these channels after the plug at the end of the tunnel has been installed. Otherwise the axial flow channels at the rock/backfill contact will remain after the sealing of the tunnel. Therefore, the materials' ability to seal channels will be further investigated.

The dry density of the 30/70-mixture reached in the field tests (1700 kg/m³) yields the following properties of the backfill /Johannesson et al, 1999; Börgesson, 2001/:

- Hydraulic conductivity with 1.2% salt content of the added water: $K = 4 \cdot 10^{-10}$ m/s.
- Compressibility: $M \sim 30,000$ kPa.
- Swelling pressure: $\sigma_s = 150\text{--}200$ kPa.

Since these values are acceptable, except for the hydraulic conductivity which is slightly too high compared to the criterion, it is concluded that the tested technique and 30/70-backfill can be used for backfilling of disposal tunnels, if the salt content of the ground water is 1.0% or lower, while 20/80 with the same compaction result (87% Proctor) yields a hydraulic conductivity that is estimated to be too high. Therefore, it remains to be studied whether the material and techniques can be improved to yield the target density and hydraulic conductivity (1E-10 m/s) also for 3.5% salinity.

Since the tests have not yet been completed and analysed it is not possible to conclude if the requirements have been fulfilled for the salt content 1% in the ground water. However, the results from the measurements made during installation and in the laboratory indicate that this is the case. Improved compaction at the roof may still be required.

3.2.3 Need for further studies

The work necessary to further investigate concept A and showing compliance with the design criteria is summarized below:

Phase 2:

1. Laboratory geotechnical investigations
The objective is to find out what density is necessary to fulfil the requirements for the optimised ballast/bentonite mixture.
2. Water inflow tests
The objective of these tests is to find out which density of the backfill is necessary to make sure that the backfill can self-heal.
3. Backfilling technique – Compaction in the tunnel.

The objective of these tests are to optimise the backfill material composition and to find out what properties the compaction equipment needs to have in order to achieve high enough density in the field.

Work foreseen for phase 3:

1. Detailed design of compaction equipment based on compaction tests.
2. Compaction tests with the developed equipment.
3. Identification of suitable compaction and rock drainage techniques for shaft filling.

3.2.4 Costs

Preliminary cost estimations for the different concepts are presented in Chapter 9. Except for the costs for research and development, the costs can be divided into 1) raw material costs and 2) investment, work, upkeep and other costs linked to processing, manufacturing and installation of the backfill material.

The basic assumptions used in the preliminary cost calculations are presented below:

Estimated backfilling rates

The estimated backfilling rates are 1.5 m/shift for the Swedish deposition tunnels and 2 m/shift for the Finnish deposition tunnels. To gain the required backfilling rates (6 m/day in the Swedish system and 10 m/week in the Finnish system), the work in the Swedish disposal tunnels needs to be done in three shifts while in the Finnish tunnels a rate of one to two shifts per day is sufficient.

Raw material

Mixture of crushed rock (70%) and bentonite (30%), either Na-bentonite MX-80 or activated Ca-bentonite from Greece.

Personnel

- One person for dismantling the tunnel infrastructure etc.
- One person for loading the transport and supervising the storage facility.
- One person for the transport to the repository level.
- One person for the transport from box feeder to deposition tunnel.
- One person for operating the backfilling equipment.
- One person for leading the shift/quality control.

For simplification of the calculations (see Chapter 9 for preliminary cost estimations) it was assumed that, on an average, two persons per shift are required for compaction of the material and dismantling the tunnel infrastructure. The personnel needed for mixing and transportation is included in the separate estimations for each task, e.g. the costs for transportation per shift includes the investment and personnel costs.

Investments

- Mixing and storage facility above ground.
- Transportation vehicle bringing the material down to the repository level .
- Box feeder for intermediate storage at the repository level.
- Transport equipment underground.
- Compaction equipment and carrier.

The investment costs listed above were taken into account in the preliminary cost estimations (Chapter 9) excluding the storage facilities for the raw materials that are assumed to be the same for all the concepts.

Compared to other concepts, concept A has low to moderate total costs depending on the type of the bentonite (Chapter 9).

3.2.5 Risk Assessment

Main uncertainties

As stated in the feasibility chapter the main uncertainty is if it is possible to improve the backfill material and the backfilling technique so that the requirements on the backfilled tunnels can be met.

The backfill material can be optimised concerning the components of the mixture, but also the homogeneity of the mixture needs to be improved.

Concerning the backfilling equipment there is a need to increase the density to find out how it can be raised by improving the backfill material and techniques, and to increase the backfilling rate.

It will also have to be determined if the stated 100 kPa in swelling pressure is enough to ensure that piping channels can self-heal in a reasonable time period.

Robustness of the concept, sensitivity to changes in design criteria

The tested backfill material emplaced with the developed technique does not comply with the requirements, both material and technique need to be improved. The A concept is very sensitive to changes in the salt content of the saturating water. This is due to the relatively low density of the bentonite in the pore system of the crushed rock.

3.3 Summary and conclusions for concept A

In concept A the entire tunnel cross-section is backfilled with inclined 20 cm thick layers consisting of a mixture of bentonite and crushed rock.

The rock is taken from the excavated tunnels and is crushed to a pre-determined grain size distribution that facilitates compaction. The bentonite and the crushed rock are mixed and the water ratio adjusted.

The material is transported with a truck to an intermediate storage located at the repository level. A special transport vehicle brings the material from the storage to the tunnel where it is conveyed to the compaction equipment by a conveyor belt or similar.

The material is pushed in place and compacted into a 20 cm thick layer with equipment developed for the purpose.

The main advantage of concept A is that it combines the low compressibility of the crushed rock with the low permeability and high swelling pressure of the bentonite. The disadvantage is that the low effective bentonite density in the backfill makes it sensitive to the salt content of the saturating ground water.

The concept complies with the design criterion concerning low compressibility. The design criterion concerning hydraulic conductivity and swelling pressure can be fulfilled if the material can be emplaced with high enough homogeneity and density. There is no indication that the criteria defined for long time stability or harmful effect on other barriers would not be fulfilled.

The conclusion is that the concept can meet the requirements if the mixing technique can be improved so that a higher homogeneity of the backfill material is achieved, and the backfilling material and technique improved so that the backfill can be placed in the tunnel with high enough density at a sufficient backfilling rate. The recommendation is that this concept should be further investigated in the next phase of the project.

4 Concept B: Compaction of swelling clay in the tunnel

4.1 Description of concept B

4.1.1 Material and Layout

The entire cross-section is filled with swelling clay (see Figure 4-1). The reference clay material is the Friedton clay but also other clays have been considered /Keto, 2003/. The material will be given a granule size distribution and a water ratio that is optimal for compaction in the tunnel.

4.1.2 Processing and mixing

Optimal water ratio and granule size distribution for compaction in the tunnel will be determined in compaction tests. The general idea is that the material shall be delivered with these properties directly from the supplier. If the material has to be re-processed before placement, the cost for the concept will rise.

4.1.3 Placement

The material is in principle applied and compacted in the same way as for concept A (see Figure 3-2 in Subchapter 3.1.3). The properties of the compaction equipment and the layer thickness will be adapted.

To compact clay is difficult and the backfilling rate is dependent on how well it is possible to adapt the compaction equipment. If this can be solved in an acceptable way the backfilling rate can be 1.5–2 m per shift.

4.1.4 Logistics

The logistics will be similar to concept A, but the original idea was that no mixing equipment would be necessary. However, a facility for storing the material above ground will be needed.

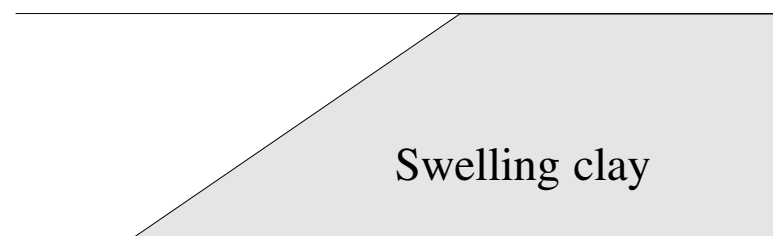


Figure 4-1. The layout of concept B.

4.1.5 Quality assurance

The quality control of the clay will be made in the following way:

The material is sampled as it is loaded on the transport from the supplier, and tested with respect to water ratio, granule size distribution, chemical (mineral) composition and geotechnical properties. The results obtained are compared to the established limit values.

The quality assurance during compaction will be made in the same way as for concept A.

4.1.6 Application of the concept for other excavations

In general the same type of considerations as described for concept A are valid for this concept. (see Chapter 3.1.6). Since the requirement to keep the buffer in place is only valid in the deposition tunnels, this concept is qualified for the other excavations if the problem of backfilling towards the roof can be solved.

4.2 Assessment of concept B

4.2.1 Fulfillment of performance requirements

Compressibility

Laboratory tests have been made in order to determine the mechanical properties of the material and to be able to calculate the vertical swelling of the buffer due to deformation of the Friedland clay /Johannesson and Börgesson, 2002/. The tests were made for the density achieved (dry density of 1400–1475 kg/m³) in field compaction tests in the Äspö HRL /Pusch and Gunnarsson, 2001/ and the conclusion was that the swelling, and thereby the decrease in density of the buffer, reached below the top of the canister, and thus failed to fulfil the design criterion concerning low compressibility. The calculation was made assuming that the buffer extends 1 m above the canister. However, if the buffer above the canister would be extended to 2.7 m, the buffer density should not be affected between the canister and the rock. More laboratory tests and calculations are required in order to determine the minimum allowable density of the Friedton clay for the present buffer dimensions. If other similar, but more promising clays than the Friedland clay are considered, the same type of tests and calculations will be made.

The concept meets the requirement concerning low compressibility if the material is emplaced in the tunnel with high enough density. The minimum density remains to be determined.

Hydraulic conductivity and swelling pressure

The results from the measurements on hydraulic conductivity made by /Johannesson and Börgesson, 2002/ are presented in Figure 4-2. The water that was used for saturation had a salinity of 3.5% (mixture of 50/50 NaCl and CaCl₂). The results indicate that the hydraulic conductivity is low enough already at a saturated density of 1900 kg/m³ (corresponding to a dry density of 1417 kg/m³). Therefore, it can be stated that the criterion for hydraulic conductivity can be fulfilled in the case if the clay can be emplaced to a saturated density of at least 1900 kg/m³.

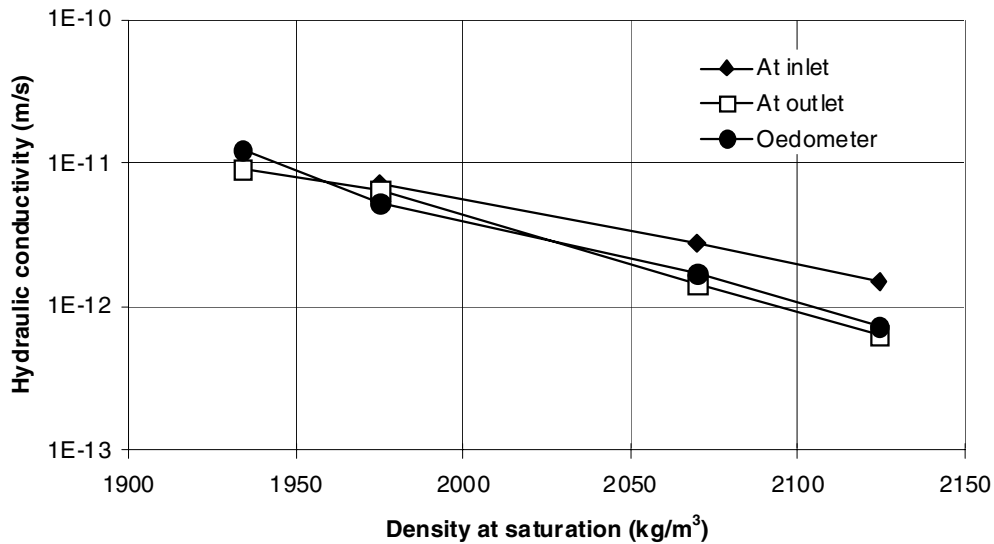


Figure 4-2. The hydraulic conductivity of the Friedland clay plotted as a function of the density at saturation. The salt content of the water used for saturation was 3.5%.

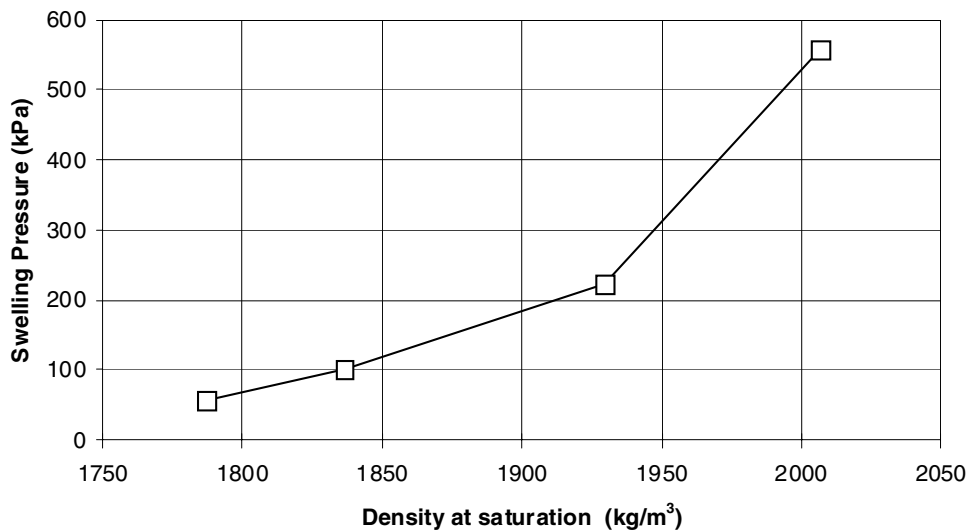


Figure 4-3. The swelling pressure of Friedton clay as a function of saturated density at a water salt content of 3.5%.

The results from the measurements of swelling pressure performed by /Johannesson and Börgesson, 2002/ are presented in Figure 4-3. The results show that clay with a density at saturation of 1850 kg/m³ will yield a swelling pressure of about 100 kPa for a salt content of 3.5% in the saturating water. The material hence fulfils the requirement concerning swelling pressure during short term measurements.

Long-term stability

No obvious risks can be identified. If the concept is considered viable, long-term safety analyses will be made in phase 3. The material is analysed in the SR-CAN /SKB, 2003/.

No harmful effects on the barriers

The risks concerning this concept are linked to compressibility, dislocation of the buffer material while possible chemical effects (potassium, sulphur) on the buffer material are deemed insignificant. The compressibility issue will be studied further in phase 2. No specific work will be directed at studying the chemical effects within this project at this stage. The material is also analysed within the SR-CAN /SKB, 2003/.

4.2.2 Technical feasibility

A test with Friedland clay backfilled by compaction in a tunnel in the Äspö HRL has been made /Pusch and Gunnarsson, 2001/. There were practical problems with the compaction of the clay, mainly due to unsuitable water ratio and granule size distribution of the delivered material. In addition, it was not possible to compact the material so that it stayed in contact with the roof. Tests for determining the optimal water ratio and granule size distribution for reaching these goals have to be made and alternative compaction techniques investigated.

A conclusion from the test was that, if the gap at the roof is not taken into account, it is probably possible to achieve a dry density of 1400 kg/m³ for suitable water ratio and grain size distribution using the compaction equipment developed for the Backfill and Plug Test.

A dry density of 1400 kg/m³, corresponding to a saturated density of just under 1900 kg/m³, would result in the following physical properties evaluated from the results presented by /Johannesson and Börgesson, 2002/:

- The requirement on low compressibility is not fulfilled, since the density of the buffer between the rock and the canister will be affected as a result of the displacement of the buffer/backfill contact. If the height of the buffer above the canister is increased to 2.7 m, the density of the buffer at the canister level would not be affected by the upward movement of the contact between the buffer and the backfill.
- Hydraulic conductivity: 2E-11 m/s extrapolated from the results in Figure 4-2.
- Swelling pressure: 180 kPa evaluated from the results in Figure 4-3.

It is probable that the Friedland clay can be compacted to a higher density. If an average dry density of 1500 kg/m³ could be achieved, this would result in a hydraulic conductivity of 10E-11 m/s and a swelling pressure of 400 kPa.

The result of the assessment is that the probability that the concept can be brought to meet the requirements in practice is high.

4.2.3 Need for further studies

There are three main issues that need to be further investigated:

1. Can the clay be compacted to a density that is high enough to keep the buffer in place for the considered time period? This will be investigated with compaction and laboratory tests.
2. Can the backfilling technique and the material be adapted or developed so that the material can be compacted all the way up to the roof? This will also be studied in the compaction tests.
3. As for all concepts, there will be problems with water inflow. The considerations for this concept are the same as for concept A. Even if the backfilling rate can be increased to 6 m/24 h a relatively small inflow of water, say a point leakage of 1 litre per minute, will probably cause piping during the backfilling. What density is necessary for the material to be able to seal channels created by piping after closure of the deposition will be investigated in laboratory tests. In principle, the rather high swelling pressure of the Friedland clay suggests that the self-healing potential is better than that of concept A.

The work necessary to further investigate concept B and methods for showing compliance is summarized below:

Phase 2:

- Geotechnical laboratory investigations.
- Compaction tests.
- Water inflow tests.

Phase 3:

- Detailed design of compaction equipment based on compaction tests.

4.2.4 Costs

Preliminary cost estimations for the different concepts are presented in Chapter 9.

In addition to the costs for research and development, the expenses can be divided into raw material costs and investment, work, upkeep and other costs linked to processing, manu-facturing and installation of the backfill material.

The basic assumptions used in the cost calculations (Chapter 9) are presented below:

Raw material

Friedton or similar natural smectitic clay.

Personnel

- One person for dismantling the tunnel infrastructure etc.
- One person for loading the transport and supervising the storage facility.
- One person for the transport to the repository level.
- One person for the transport from box feeder to deposition tunnel.
- One person for operating the backfilling equipment.
- One person for leading the shift/quality control.

For simplification of the calculations (see Chapter 9) it was assumed that, on average, 2 persons per shift are required for compaction/dismantling of the tunnel infrastructure. The personnel needed for mixing and transportation is included in the separate estimations.

Investments

- Storage facility above ground.
- A vehicle for transporting the material to the repository level.
- Box feeder for intermediate storage at the repository level.
- Underground transportation equipment .
- Compaction equipment and carrier.

The investment costs listed above were taken into account in the preliminary cost estimations (Chapter 9) excluding the storage facilities for the raw materials that are assumed to be the same for each concept.

According to the preliminary costs estimation (Chapter 9), concept B has moderate total costs compared to other concepts. The raw material costs for concept B are slightly higher than for concept A. The other costs are the same magnitude as for concepts A and C.

4.2.5 Risk assessment

Main uncertainties

1. Can the material be compacted to a sufficiently high density to fulfil the requirement of low compressibility?
2. Can the material be compacted so that it stays in contact with the roof?

These issues will have to be tested. The experience from the compaction of crushed rock/bentonite mixture showed that it is possible to compact a cohesive material this way. The judgment is that there is a fair possibility that this can be made also for pure clay. The option is to fill the void at the roof with pellets or blocks.

3. Can high water inflow be handled?

High water inflow will probably lead to piping in the backfilling phase. Like for concept A, water flow over the sloping surface would cause great difficulties and has to be avoided. If the water inflow cannot be decreased to an acceptable level by grouting, engineered solutions such as drip protection and drainage can be developed. To be able to use drainage pipes in the material, the swelling ability of the material has to be such that it can expand into the drainage pipe and seal it after the saturation phase is over. The sealing can be facilitated if clay based-slurry, or pellets, be injected into the drainage system.

How sensitive is the concept to changes in the interpretation of the requirements? How robust is the system?

1. Based on the tests of hydraulic conductivity and swelling pressure with 3.5% salt content in the saturating water and on the results from the field tests, the Friedton clay seems to offer quite a good margin with respect to the requirements even if these are sharpened, i.e. concerning the groundwater salinity. This is not the case for the compressibility. In order to make sensitivity analyses, tests where the influence of the salt content on the swelling pressure, hydraulic conductivity and compression have to be made.
2. The requirement that the swelling pressure must be at least 100 kPa for sealing channels created by piping during installation can probably be fulfilled and the concept can be considered to be fairly robust also in this respect.
3. Other open issues regarding the various requirements will mainly be handled within the SR-CAN /SKB, 2003/.

No other major sensitivity to changes in the design criteria has been identified.

The judgment is that the uncertainties are acceptable for continuing the investigation of the concept. The listed uncertainties will be eliminated by further research and development listed in Subchapter 4.2.3.

4.3 Summary and conclusions for concept B

Concept B is based on in-situ compaction of swelling clay and the Friedton clay is used as reference backfill material. It is assumed that the material can be delivered with water ratio and granule size distribution that are suitable for in-situ compaction. The material is emplaced and compacted with the technique developed for concept A. The equipment and the layer thickness will be adapted.

The backfill material is transported to the deposition level with trucks, stored intermediately under ground and then transported to the deposition tunnel. This transport is probably made with a specially designed vehicle.

The material is compacted to 15–30 cm thick layers with an approximate slope inclination of 35 degrees.

The main advantages of the concept are that the material can be compacted under field conditions to a density that results in a sufficiently low hydraulic conductivity also at a ground water salinity of 3.5% TDS (50% CaCl₂ and 50% NaCl). The main disadvantages are that the density achieved in the field tests did not result in a sufficiently low compressibility and that the material could not be compacted to stay in contact with the roof. If the material can be optimised with respect to water ratio and granule size distribution, and the compactibility can be further improved the chances are good that high enough density can be achieved over the entire cross-section of the tunnel.

Concept B fulfils the design criteria concerning hydraulic conductivity and swelling pressure for the service time of the repository. The density in the field test does not fulfil the design criterion concerning compressibility but there is a fair chance that the density achieved with in-situ compaction can be increased and the compressibility of the material thereby decreased. Concerning the technical feasibility, tests for determining the optimal water ratio and granule size distribution for compacting the clay so that it stays in contact with the roof and so that the optimum density is achieved should be made. The compaction equipment has to be adapted or developed.

If the density can not be raised enough to fulfil the compressibility requirement, the concept would probably be suitable for all other excavations since the compressibility requirement is only valid in the deposition tunnels.

The conclusion is that there is a high probability that the concept can be developed to meet the requirements and that further work should be directed at this in the next phase.

5 Concept C: Compaction of non-swelling soil type in the tunnel with bentonite blocks at the roof

The aim of this chapter is to describe and evaluate concept C, for which the main part of the tunnel is backfilled with a non-swelling soil type with low hydraulic conductivity. The evaluation is based on requirements and design criteria introduced for backfilling of disposal tunnels (see Chapter 2.2). The concept may also be used in other parts of the repository.

5.1 Concept description

5.1.1 Materials

Originally this concept was supposed to be based on compaction of non-swelling clay in the tunnel with bentonite blocks placed in the roof section. However, in a study evaluating the suitability of different clays and soil types for different concepts /Keto, 2003/ it was stated that non-swelling clay did not have suitable material properties for the type of compaction possible in the tunnel. Therefore it was suggested, that concept C could be based on fine-rich basal till of glacial origin instead. This material has very unsorted grain size distribution resulting in low porosity (10–20%) and good compaction properties. The hydraulic conductivity of fine-rich till is only slightly higher than the target value, and therefore approximately 5 weight-percent of bentonite is added into the material in order to gain the hydraulic conductivity of lower than $1\text{E-}10$ m/s. The aim of the bentonite addition was not to make the bulk material expandable. The geological origin, occurrence and material properties of a fine-rich till are described in /Keto, 2003/.

The bentonite used for the mixture and for the blocks can be either Na-bentonite or Ca/Mg-bentonite. The material properties of bentonite and the differences between various commercial bentonites have been discussed e.g. in /Pusch, 1994; Pusch, 2001; Keto, 2003/. Powdered bentonite is recommended for the mixture in order to gain homogeneous distribution of the clay, while granular bentonite is suitable for block production in order to avoid formation of air-filled voids in the blocks.

Approximately 5–10% of the total tunnel volume is backfilled with pre-compacted bentonite blocks placed at the roof of the tunnel. Taking into account the amount of bentonite in the mixture and in the blocks the bentonite-till ratio is approximately 10:90 or 15:85.

5.1.2 Processing and mixing

The till is excavated with a large excavator or in extreme cases by blasting. The maximum excavation depth depends on the thickness of the till formation, usually 2–10 m, and on the properties of the excavation environment. Depending on the moisture content and the grain size distribution of the till which ranges between colloidal particles and large boulders, the material is screened and/or crushed after the excavation. The crushed tills are generally coarser and well sorted than the screened tills. The maximum grain size should not be larger than 3–5 cm in order to ensure effective mixing process and homogeneous end product.

To gain a homogeneous mixture, the till has to be relatively dry and wetting of stored material must be avoided. Many dense tills are sufficiently dry to be used without drying, while shallow moraines may have to be processed, for there are several ways to reduce the water content. Storing the material in large piles actually decreases and evens out the moisture content of the till with time. In addition, the till can be dried effectively by spreading it over the ground surface if the weather conditions are suitable. Other less economical possibilities to dry the till are to mix together dry and wet material or to use drum drier or blower for the job. Storage is preferably made in large piles which should be covered to prevent establishment of vegetation.

The mixing of bentonite and fine-rich till is done in a modified concrete plant mixer. Similar mixing plants are used for mixing of bentonite-based materials for landfill sealing structures. The proportions of each component of the mixture (till, bentonite, water) is determined in the laboratory. This is repeated regularly to ensure that possible variations in the composition of the till do not affect the quality of the end product. The principle of the mixing plant is presented in Figure 5-1. There are separate silos for the till, bentonite and water. The till is fed to the mixer by help of a conveyor placed underneath the till silos while the bentonite is provided by a silo placed above the mixer. The feeding of bentonite to the mixture is gradual in order to gain homogeneous mixing product. The dry components are mixed to a homogeneous mixture before any water is added. The water is added as a misty shower and the mixing continued until the material is homogeneously moist. The process is fully automatic and staff is needed only for surveillance of the process and for filling the material silos. For quality assurance reasons, the water content of each batch is determined in the field-laboratory located in the control centre by the staff. The total mixing time, including loading and the actual mixing, depends on the capacity of the plant that depends on the type and size of the mixer. For example some environmental constructors use relatively small mixing plants with capacity of approximately 30 m³/h (50 t/h), while bigger plants with maximum capacities of 75m³/h and 150 m³/h have also been used.

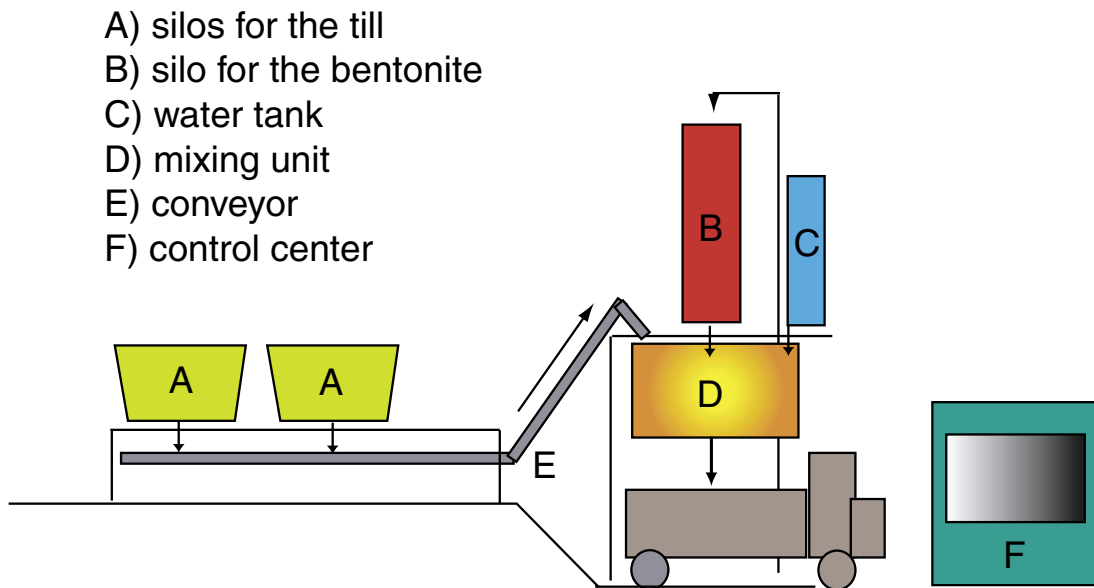


Figure 5-1. Principle of the mixing process.

Achieving a good homogeneity in the mixture would be a challenge. It may be necessary to dry the till before adding the bentonite and this would be costly. The capacity of the mixing plant should be chosen according to the required backfilling rate. This means that a smaller mixing plant is required in the Finnish system compared to the Swedish system. However, it should be noted that the capacity of the mixing plant is also linked to the homogeneity of the mixing product and this should be also taken into consideration when choosing the plant.

In principle, it is possible to produce “synthetic fine-rich basal till” with the same mixing plant. Synthetic till can be produced from different grain-size fractions of crushed rock and by adding fineries (silt and clay) to the mixture. In practice, the till silos are filled with different fractions of crushed rock and soil and the system is programmed to produce synthetic till with certain fixed grain size distribution mixed with bentonite. However, the grain shape of the synthetic till may be different from that of natural till, which can lead to different physical properties.

5.1.3 Production of blocks

It is assumed that the backfilling blocks cannot be manufactured in the same facility as the buffer blocks. For example, the press used for pre-compaction of big buffer blocks is not suitable for manufacturing small ones, and special moulds need to be designed and manufactured. The block storage should be large enough to host both buffer and backfilling blocks. The relative humidity of the storage needs to be adjusted to suitable level (50–70%) in order to avoid degradation.

The process of producing bentonite buffer blocks for the Prototype Repository has been described in /Johannesson, 2002/. Another possibility that has been considered is the production of small (brick) size blocks for buffer. Such small brick size blocks could also be applied for backfilling purposes.

5.1.4 Compaction of backfill and placement of blocks

In principle, the till/bentonite mixture can be applied and compacted in inclined layers as in concepts A and B according to the following procedure:

1. Moving the material into the tunnel with a bucket loader or similar.
2. Pushing the material in place with a tool designed for the purpose.
3. Compacting the layer with a vibrating plate.

There are several uncertainties concerning the technical feasibility of this concept (see Figure 5-2). For instance, the narrow width of the tunnels means that there is not enough space for the vehicles to turn. To some extent, this may affect the backfilling rate. In order to enhance the efficiency, a system bringing the backfill material past the spreading/compaction vehicle can be developed. This can have the form of a conveyor belt running through the compaction vehicle as suggested by /Kirkkomäki, 1999/.

The process of compaction of a mixture of bentonite and crushed rock in inclined layers in a tunnel has previously been tested in the Äspö HRL in the projects *Field test of tunnel backfilling, Backfill and plug test and the Prototype repository* /Gunnarsson et al, 2001a; Gunnarsson, 2002/. The same kind of backfilling technique can be used for compaction of till-based backfill. The achieved density for the bulk material and for the bentonite phase within the mixture is, however, supposed to be higher for the till-based material than for the mixture of crushed rock/bentonite /Keto, 2003/ because of the differences between the material properties of these materials, which have to be determined in the laboratory and in the field. Like for concepts A and B a too high water inflow affect the compaction result due to surface erosion.

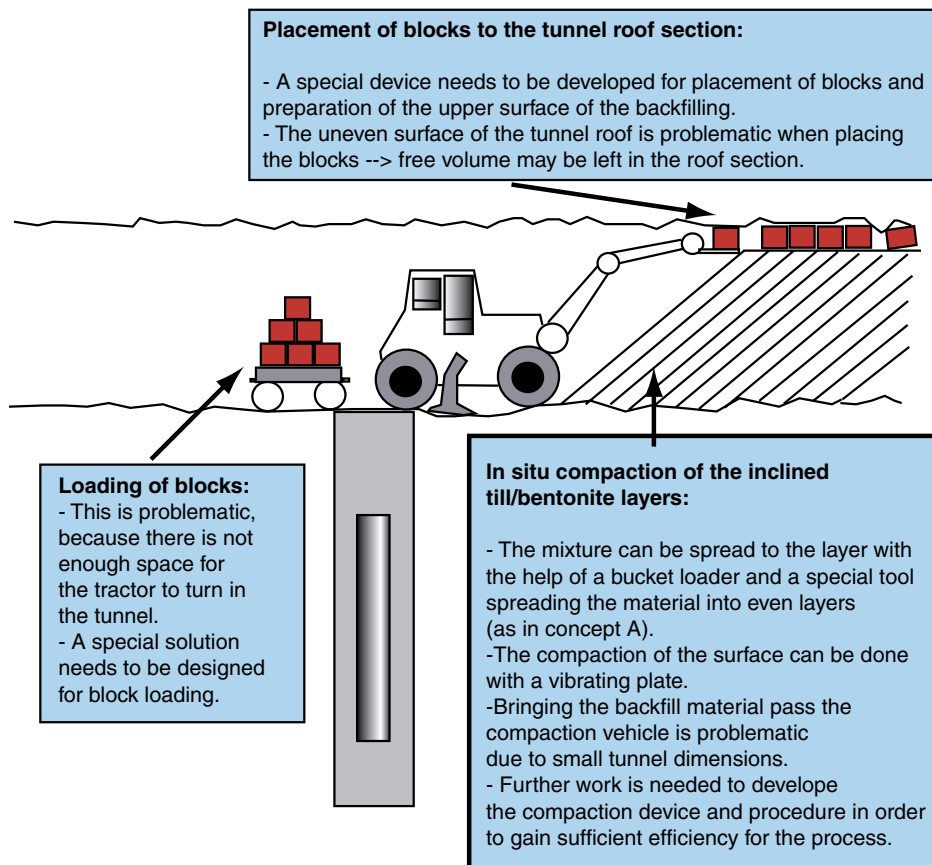


Figure 5-2. Uncertainties linked to technical feasibility of concept C.

Vibration-based compaction techniques may not be the optimal for a till-based backfill because of the cohesiveness of the material. According to /Terzaghi and Peck, 1967; Terzaghi et al, 1996/, the compacting effect of vibration decreases greatly with increasing cohesion, because the electrical forces between the finer particles prevent the particles to move into more stable positions. Therefore, sheep or pad-foot rollers should be considered for the compaction. Depending on the water leakage situation, the bottom of the tunnel can possibly be applied and compacted in horizontal layers with a roller compactor.

After compaction of the inclined layers, the upper surface of the backfill needs to be evened out and possibly shaped to a suitable form depending on the geometry of the blocks (Figure 5-3). After this the blocks can be placed at the roof with some kind of special placement tool, which remains to be developed. Another possibility is to install the blocks manually. Manual placement of brick-size backfilling blocks has been tested within the Backfill and Plug test in Äspö /Gunnarsson et al, 2001a/. A preliminary plan for a placement tool for installing pre-compacted blocks has been described within concept description of the backfilling concept D. This equipment and method is, however, not directly applicable to concept C. In any case the placement would most likely be problematic because the roof surface of tunnel excavated with drill and blast technique is uneven and the deviation is be approximately 10–15 cm and even 20 cm in extreme cases (see Figures 5-2 and 5-3). Therefore, there would be gaps between the blocks and the roof and also between adjacent blocks. This requires additional filling of pellets or clay powder in the voids for reaching a sufficiently high average density and expandability. The placement is made by grouting/blowing the pellets into the voids or by applying underwater cast concrete technique. Naturally, TBM-drilled tunnels offer less difficulty in this respect. If TBM-technique is used, the floor section needs to be filled and evened first (cf Figure 5-3).

The question of handling different materials in the tunnel has to be further investigated. It seems that various types of equipment will be necessary for performing the transportation of materials, compacting of the mixture and placing blocks and pellets at the roof. The complexity of the process slows down the backfilling rate of this concept compared to concepts A and B.

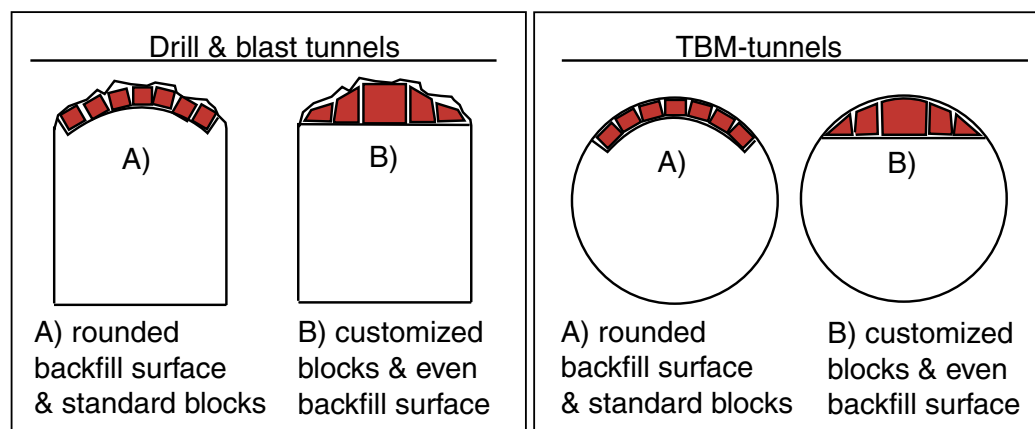


Figure 5-3. The dependence of the shape of the pre-compacted blocks on the compacted backfilling. If the upper surface of the backfill is even, the blocks need to be shaped to fit with the tunnel roof. Most likely, it is easier to fill the roof section with blocks if the tunnel has been drilled with a tunnel-boring machine (TBM).

5.1.5 Logistics

The purchased bentonite needs to be transported to the bentonite storage and from the storage to the pre-compaction facility and the mixing plant. The fine-rich till is transported from the occurrence to storage piles next to the mixing plant. The material can be moved from the storage to the mixing plant silos with a front end loader.

The mixture of fine-rich till and bentonite, and the bentonite blocks are prepared above ground and transported to the deposition tunnel via access tunnels or, alternatively, via shafts. Transportation through access tunnels would be the most efficient and convenient way of bringing backfill mixture to the repository level because of the large volumes involved. However, it should be considered whether bentonite blocks should be transported by elevator for avoiding breakage and degradation.

The transportation vehicle for the mixture can be a regular truck or a tank truck commonly used for transportation of concrete in mines. The material can be either directly transported to the disposal tunnel or alternatively to a temporary storage placed in the repository level near the backfilling site. The temporary storage can be a movable silo, from which the exact amount of material needed for one layer is loaded onto a special vehicle (truck or similar) for transportation to the disposal tunnel.

The blocks can also be stored temporarily on the repository level. However, it is recommended that bentonite blocks be stored underground only for short time periods to avoid changes in the water content and associated degradation if proper facilities are not available underground. The vehicle for block transportation should provide easy and flexible loading and unloading of the blocks.

5.1.6 Quality assurance

Quality assurance is part of the whole backfill process starting from purchase of materials to the point where the whole repository has been backfilled and sealed. The basic properties of the materials are tested regularly with simple field test methods for each batch of material and with more thorough laboratory tests, e.g. every 6–12 months and when necessary according to the field test results. The regular field tests for purchased bentonite include at least:

- Determination of the water ratio.
- Free swelling volume test.
- Determination of the liquid limit.
- Methylene blue test (an alternative and complementary test method for swelling volume test and determination of liquid limit).
- Visual inspection of the granule size distribution, amount of stones in the material and colour.
- Possibly also determination of the granule size distribution.

First three methods mentioned above have been described in /Pusch, 2002/. The thorough laboratory test includes determination of the mineralogy and geochemistry of the material together with some time-consuming geotechnical tests (e.g. hydraulic conductivity).

The grain size distribution of the fine-rich till is tested regularly by dry sieving and aerometric/laser methods. It is important that the till composes at least 5% of clay sized particles ($< 2 \mu\text{m}$) and 30% fines (grains smaller than 0.06 mm) and that the grain size distribution is unsorted (almost straight and gently dipping grain-size curve). The content of organics should be less than 1%. This is determined as loss on ignition.

The water content of the mixture is determined from each mixed batch and if the water content is too high or too low compared to the specifications, the batch has to be reprocessed. Due the possible variations of the till component the compaction properties and optimum water content is also re-determined regularly in the laboratory by Proctor compaction test or ICT-tester. Thorough characterization of material properties, including e.g. the grain size distribution and other basic geotechnical and mineralogical parameters, should also be made for the till from time to time.

The water content and shape of the blocks need to be controlled and surveyed after the compaction, during storage and before installation. Broken bentonite blocks are crushed, dried, reprocessed and used as raw material for the blocks.

The density of each compacted layer is systematically measured in the field. Samples for laboratory determination (density and water ratio) are taken systematically (every 5–10 m spacing) in order to validate the field measurements and to calibrate these. This is also the case with layers that have been wetted by inflowing water. Layers with too low density are removed and replaced by new ones.

The placement of blocks will have its own quality requirements. If there are too large gaps between neighbouring blocks and/or between blocks and the roof, or if the blocks have fractured during the placement, they may have to be removed and replaced by new ones. The maximum allowable gap between adjacent blocks can be set at 3 mm for easy emplacement. The gaps would disappear during the saturation process. The density of the blocks and the free space between the blocks and the roof need to be dimensioned to gain high enough density, i.e. approximately 1950 kg/m^3 at saturation also after the saturation phase.

5.1.7 Applicability in other parts of the repository

Compaction of fine-rich till mixed with 5% bentonite in the tunnel can also be used for other parts of the repository, e.g. in the access tunnel, the central tunnel and auxiliary rooms, where larger and more efficient compaction devices can be used. Here, the backfilling rate should be higher than for disposal tunnels. The placement of blocks on top of the inclined layers may be unsuitable and may have to be replaced by pneumatically placed bentonite pellets. Some strategically placed bentonite plugs can be used to ensure the long-term performance of the system, e.g. at the end of the shafts and access tunnels. The shafts can also be backfilled with till-based material, but the compaction technique would be different than the one used in horizontal and sub-horizontal tunnels.

5.2 Assessment

5.2.1 Fulfillment of performance requirements

Compressibility

The compressibility of the till-based backfill is very low and its low porosity means that loss of clay from the buffer into the voids of the backfill is not expected. However, the compressibility and porosity of the material should be studied in laboratory to verify this assumption. It is assumed that the compression modulus of the bulk material of concept C is the same as for concept A, i.e. > 10 MPa. The backfill of the roof interacts with the till-based backfill in the same way as the buffer.

Hydraulic conductivity and swelling pressure

The low hydraulic conductivity of the mixture is due both to the 5% bentonite added to mixture, and to the very low porosity of the fine-rich till. The hydraulic conductivity of suitable till without any bentonite added is usually order of 1E-9 m/s. However, with only small amounts of bentonite added to the mixture, it is possible to reach the target conductivity. Very low hydraulic conductivities (5E-12 m/s) have in fact been reached for such till-based mixture under fresh water conditions. However, the hydraulic properties of the mixture in saline water up to 5% NaCl/CaCl₂ need to be tested in laboratory. It should be emphasized here that the bentonite is added to the bulk material to gain low enough hydraulic conductivity and not to gain swelling ability. The mixture may exert some swelling pressure due to the bentonite component, but it would be lower than 100 kPa. This requires further studies in the laboratory.

The bentonite blocks in the roof section should have a density of approximately 1950 kg/m³ at saturation in order to fulfil the requirements set for the hydraulic conductivity and a swelling pressure of at least 100 kPa in salt water. In a tunnel excavated by drill and blast the probability of large voids between the blocks and the roof is considerable, which, in the worst case may lead to unacceptably low bentonite density after saturation. Depending on the size of the voids the free space remaining after block placement in the roof section may have to be injected with bentonite pellets. In order to maintain sufficient bentonite density in the roof section, the degree of block filling of the roof section should be at least 90%.

Long-term stability

The fine-rich till would be physically stable in deep repositories, although some minor mineralogical alteration, e.g. conversion of mica minerals to clay minerals is possible. The long-term stability of pre-compacted bentonite is supposed to be good, considering also cation exchange and illitization. These matters have been and will be studied further in other SKB and Posiva projects /Posiva, 2000; Posiva, 2003; SKB, 2001/.

Harmful effects on the other barriers

The components used in the mixture are not believed to have any noticeable harmful effect on the other barriers in the deep repository. However, the geochemical properties of the fine-rich till need to be characterized to verify this assumption. The interaction between the buffer bentonite and the rock, other barriers, groundwater and foreign materials will be studied in other SKB and Posiva projects /Posiva 2000; SKB 2001/.

5.2.2 Technical feasibility

The problems linked to the technical feasibility of concept C have already been discussed in Chapter 5.1.4, but the key issues will also be summarized in this chapter. In principle, proven technology can be applied at least to manufacturing and compaction of the bulk backfill material. According to preliminary estimates, the backfilling rate of the bulk backfill is sufficient for both the Finnish and Swedish cases. The bulk material is supposed to have optimal compaction properties, but the net density needs to be tested with compaction method suitable for tunnel conditions (see Chapter 5.2.3). However, it can be stated that the usage of till-based mixture as a backfill material does not require very much further technical development.

The placement of blocks is supposed to slow down the backfill rate remarkably, especially in the case of tunnels excavated by drill and blast technique. In principle, the installation can be done manually or with a special tool. Such a tool would require further technical development work and testing. Another solution is that the roof section is filled up to the roof with the bulk backfill and the backfilling completed by injection of bentonite pellets with high pressure trough pipes in the roof section. The resulting properties for such backfill in the roof section would, however, require testing and modelling to verify the safety of the system in a long-term perspective. The advantage of using pellets would be a high efficiency in the backfilling operation. The bulk dry density of bentonite pellets at placement is only 1.3–1.5 t/m³, but these densities may be high enough (information from NAGRA). Further results are needed to verify this opinion.

The technical feasibility of the mixing operation is a critical issue, since the 5% of bentonite needs to be very homogeneously distributed in the mixture. For this purpose the till has to be very dry when the bentonite is added and the mixing has to be very effective requiring an Eirich type mixer. Reducing the water content of the till may be very costly.

The resistance of the till-based material to internal erosion is supposed to be relatively good due to the self-filtering nature of the material /Keto, 2003/. The risk of piping is highest for materials composed of coarse ballast grains with a uniform grain size and fine particles filling the voids of the coarse grain skeleton. This is not the case for a till-based backfill. However, if piping would for some reason occur, the material would have only limited self-healing capacity compared to smectitic clays. Therefore, the resistance of the material against piping should be studied in laboratory. The backfilling blocks are supposed to have enough self-healing capacity to heal flow paths after the saturation stage.

Another practical issue is the availability, resources and homogeneity of the basal till, which is a natural common soil type in Northern countries. Exploiting soils on a large scale requires permission from the authorities respecting also effects on the environment.

5.2.3 Need for further studies

This concept description is only very preliminary and includes several uncertainties (see Chapter 5.2.5). In order to proceed with this concept, the following studies and development work are recommended:

- The most important study required in order to evaluate the feasibility and long-term safety of this concept, is to test the basic geotechnical properties of the till-based mixture saturated and percolated by salt water (3.5–5%). If the bulk material fails to perform acceptably the concept should be dropped.
- If the laboratory studies give hope for this concept, the achieved density for the inclined layers can be tested by small-scale field compaction tests using 5–10 t of the material mixed and compacted with a vibrating plate to form a few inclined layers on a stiff base. The test can be made in cooperation with landfill contractors already having the technique with mixing plant, compaction devices and the experience needed for the test.
- The self-healing capacity of the system needs to be studied in the laboratory and under field conditions.
- Gaining more information on the experience on the similar materials used in landfill projects.
- Finding suitable sources of fine-rich till within reasonable distance from the repository sites. Testing of the basic mineralogical and geochemical properties of the potential material.
- Studies on the manufacturing and placement of blocks.
- Alternative studies on the usage of pellets in this concept.
- Synthetic till, can it be manufactured from crushed rock?

5.2.4 Costs

In addition to costs for development expenses are caused by the raw material, personnel, and investments. There would be also energy, quality assurance, upkeep and insurance costs, but they are moderate or low. The purpose of this subchapter is to list major cost issues and estimate the cost levels. The preliminary cost estimations for different concepts are presented in Chapter 9.

Fabrication

Production of blocks can be made either continuously in one shift per day, or in campaigns with three shifts per day. Mixing of the till-based backfill material and transportation of the backfill materials to the repository level is done in 1–3 shifts depending on the need of backfill material per day and the capacity of the mixing plant.

Raw materials

Fine-rich till is purchased from a subcontractor, who is responsible for excavation, pre-processing (e.g. sieving), quality checking, and transportation of the material to the repository site (Olkiluoto or a similar site in Sweden).

Bentonite, including re-processing and transportation to the site, is purchased from an exporter or directly from a producer. The bentonite used in the preliminary cost calculations was activated Ca-bentonite from Greece.

Personnel

The assumed need for personnel for block production is approximately 2 persons per shift. Only one shift per day is needed for producing the blocks for the Swedish system. Due to the low backfilling rate of the Finnish system, it is recommended that the manufacturing of the blocks be done in campaigns.

The mixing of backfilling materials requires 1–2 persons/shift of which one is responsible for transportation and loading of the raw materials to the mixing plant silos and the other for controlling the process and quality assurance. If the volume of the silos is large enough, the loading can be done in one shift per day. The quality assurance person must be present during the whole mixing process. In the preliminary cost estimation (Chapter 9) the personnel costs and investment cost for the mixing plant are included in the estimation on the mixing task (20 Euro/m³).

One person/shift is required for transportation of pre-compacted blocks and backfill to the deposition tunnel or, alternatively, to a temporary storage located on the repository level. If temporary underground storage is applied, one person/shift is continuously needed for transportation of backfilling materials from the temporary storage to the deposition tunnel. In the preliminary cost estimation (Chapter 9), the transportation cost estimation 400 Euro/shift includes also the personnel costs for transportation.

One to two persons/shift are needed for dismantling the infrastructure from the tunnel, operating the equipments needed for moving the backfill material, compaction of the layers, preparation of the upper backfill surface and placing the blocks. In addition, one person/shift is required for being in charge of the underground shift and for quality control. In the preliminary cost estimation (Chapter 9) it is assumed that, as an average, 2 persons per shift are required for removing earlier installations and for compaction of the backfill.

As a summary the minimum need for personnel per one shift in concept C is:

- Continuously two persons per shift for above ground operations.
- Continuously one person for transportation of materials.
- Continuously two persons per shift for underground operations.
- Continuously/temporarily two persons per shift for block production.

Backfill rate

As a case example, the distance between adjacent deposition holes in Olkiluoto is approximately 10 m and the disposal rate is relatively slow with approximately 40 canisters per year, i.e. 3–4 canisters per month. The maximum required backfilling rate is therefore only 140 m³ (solid cubic volume) per week or 10 m/week assuming a cross-section area of 14 m². The capacity of the mixing plant is much higher than this, i.e. a minimum of 30 m³/hour and 240 m³/working shift, with a density of 1670 kg/m³. Therefore, there is no need to use the mixing-plant in all three shifts. However, in the Swedish system, the mixing may be done in three shifts. In the Swedish case the compaction of the inclined layers and placement of blocks need to be done in three shifts while in the Finnish system only 2 shifts/day is required.

The estimated backfilling rates for the bulk backfill used in preliminary cost estimation calculations are 3.2 m for the Finnish disposal tunnels and 2.25 m for the Swedish disposal tunnels. The estimated installation rate of the backfilling blocks in the roof section is 1.75 m for both cases, assuming that the installation can be done manually or semi-manually.

Investments

The equipments used for backfilling generates considerable investment costs, especially the block manufacturing. In some cases it may be advantageous to rent the equipment or to buy the service e.g. mixing of the backfill from a subcontractor, especially if the work is done periodically. The investment costs that are underlined in the following list imply significant design and development costs.

- Mixing plant.
- Pre-compaction facility, mixing equipment, pre-compaction press and moulds.
- Storage facilities for the bentonite, bentonite blocks and till (+ possibly an underground silo for the mixture.
- Transport equipment for bentonite, bentonite blocks and mixture.
- Underground transport vehicles.
- Compaction equipment.
- Equipment for placing the blocks (if not made manually).
- Equipment for grouting bentonite pellets.

The preliminary cost estimation in Chapter 9 includes the investment costs for a block pressing plant, and storage facilities for the blocks and special carriers. The installation is supposed to be done manually. The mixing and transportation costs are included in the separate estimations. The need for storage facilities for the raw materials was not taken into account, but they are supposed to be the same in all concepts.

According to the preliminary cost estimation (see Chapter 9) the total costs for concept C seems to be lower than for all other concepts. The difference is mainly due to low material costs. The other costs are the same order as for concepts A and B.

5.2.5 Risk assessment

The most crucial uncertainty of this concept is linked to the geotechnical properties of the bulk backfill material under saline conditions for which further studies are needed. Another risk is linked to the availability and homogeneity of the basal till, which may represent a problem although the geological distribution of the soil type is extensive in Nordic countries.

The bulk material would have very limited swelling capacity, which raises the following questions:

- Is the interface between the non-swelling backfill and the tunnel walls tight enough to exclude advection in this boundary zone?
- What is the ability of the bulk material to prevent piping and to self-heal after the tunnel has been plugged?
- What is the role of the bentonite blocks installed to the roof section in respect to the processes mentioned above?
- Is the usage of non-swelling materials against the basic requirements set for backfilling?
- What is the settlement by consolidation of the backfill in and after saturation with water?

Another uncertainty is the technical feasibility of block placement that requires further development work to reach the sufficient backfill rate also for the Swedish system. However, the effectiveness of the backfilling procedure is of secondary importance when assessing the long-term safety of the system.

In principle, till-based backfill represents a robust backfill system that ensures stable environment for the buffer bentonite in a long-term perspective, even in the case of significant changes in the disposal environment. Due to the low compressibility and porosity of the bulk backfill material the risk of buffer intrusion is minimal. In addition, the bulk material would still have relatively low hydraulic conductivity, in the order of $1\text{E-}9$ m/s even if the bentonite component of the mixture fails to perform in high salinity. The robustness of a backfill system is of course dependent on how successful the installation of the backfill has been with respect to homogeneity and density.

5.3 Summary and conclusions for concept C

Backfilling concept C is based on compaction of a non-swelling soil type, i.e. fine-rich till with a small addition of bentonite, in place in the tunnel. Pre-compacted bentonite blocks are installed at the roof. The bulk material has a very limited swelling capacity and therefore bentonite blocks are used in the roof section in order to ensure tight contact between the backfill and the rock.

The till-based backfill material is mixed above ground surface in a modified concrete mixing plant. The backfilling blocks are pre-compacted in a facility above ground. Special moulds are needed to manufacture blocks fitting the profile of the tunnel roof.

The mixture is transported to the repository level via access ramp in a tank truck. Bentonite blocks can be transported via access ramp or, alternatively, via shaft in order to avoid breakages. Due to the narrow width of the disposal tunnels, bringing backfilling material past the compaction/placement device may require development of special equipments in order to enhance the efficiency of the backfill procedure.

The mixture is compacted to form inclined layers with a thickness of approximately 15–30 cm. The compaction is made with a vibrating plate. Alternatively, in dry tunnel sections the bottom section of the tunnel can be compacted to horizontal layers with a roller compactor. Placement of blocks in the roof section is a technically challenging task. The upper surface of the backfill needs to be prepared for the placement of blocks, which is difficult if the roof surface is uneven as in tunnels excavated with drill and blast technique. Special equipments may have to be developed for block placement or done manually. It should be checked whether the blocks can be replaced with pneumatically injected bentonite pellets in order to increase the backfilling rate.

Quality assurance is a part of every step of the backfilling process starting from purchase of the materials to the sealing of the repository.

The costs of concept C (Chapter 9) are lower than for the other backfilling concepts considered, even when including the cost for block manufacturing and placement. This is mainly due to remarkably lower material costs than in any other concept.

The till-based backfill may also be used in the other parts of the repository such as the access ramp, central tunnel, shaft and auxiliary facilities. Use of blocks in the roof section may not be necessary in the other parts of the repository. The blocks can be replaced with bentonite pellets and the long-term performance of the system can be secured by some strategically placed long-lasting plug structures.

It is likely that concept C fulfils the criteria concerning low compressibility, long-term stability and possible harmful effects on the other barriers. The hydraulic conductivity of a till-based material is supposed to be very low, but the hydraulic properties need to be tested also for high salinity. The till-based material may have some swelling capacity, but the magnitude needs to be checked in laboratory. It is more likely that till-based backfill, with the limited density that can be achieved with the proposed compaction technique would undergo compression under its own weight in the course of water saturation. Furthermore, the lack of swelling pressure means that the self-healing capacity to seal off piping-induced channels would be insufficient. The bentonite placed in the roof section may however compensate for the low swelling ability of the bulk backfill, provide a tight contact at the roof, and somewhat restrict the longitudinal advection between the backfill and the roof. From a technical feasibility point of view, placement of blocks may be time-consuming.

Despite the assumed advantage of low cost concept C includes major uncertainties, mainly concerning the ability to seal piping induced channels, and therefore it is recommended that the concept will not be studied further in the next phase of the project.

6 Concept D: Pre-compacted blocks in the entire tunnel cross-section

6.1 Description of concept D

6.1.1 Material and layout

The layout of concept D is shown in Figure 6-1. The entire cross-section is filled with pre-compacted blocks. If needed the remaining gaps can be filled with bentonite pellets or granules. The floor has to be levelled to provide a stable base for the blocks and to facilitate transport. This can probably be made by compacting suitable clay that fulfils the requirements on low hydraulic conductivity and that is relatively insensitive to the water that will pass from the inner part. Another solution would be to use a perforated steel plate at the floor. The steel plate would provide a stable foundation for the blocks. It would also act as drainage during the installation so that the water from the inner part of the drift would run under the plate. Once the sealing plug for the deposition tunnel is in place, the water will fill all voids and the clay will swell through the holes under the plate and seal the tunnel cross-section completely. This is also the principle for the KBS-3H concept and experience from tests made for this concept could be utilized.

A number of different types of materials are considered for concept D a few examples are listed below:

- MX-80 or, Milos or Indian bentonite.
- Friedton or other swelling clay.
- Different types of mixtures of ballast and bentonite.

6.1.2 Processing and block pressing

The chosen material is delivered with a water ratio and granule size distribution suitable for block pressing. The general feasibility to manufacture mechanically stable blocks from different materials will be investigated in block compaction tests in phase 2 of this project. If the backfill material cannot be delivered with the specified water ratio, or if a material consisting of ballast and clay is used, the material will be mixed before the block pressing.

A block pressing plant will be built at the repository site. The blocks will be placed on pallets and kept in storage with controlled humidity.

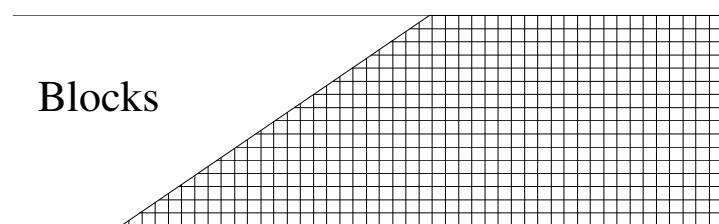


Figure 6-1. The layout of concept D.

6.1.3 Logistics and placement

The pallets with the blocks are placed on a truck and transported to the deposition tunnel. From the transport truck the pallets are moved onto a specially designed transport that moves the pallets to the backfilling front. One alternative for the block placement is presented in Figure 6-2 to 6-5.

The placement equipment is made up of two units, a transport unit and a placement unit (Figure 6-2). Both are equipped with conveyor belts so that pallets can continuously be brought forward. The transport unit moves into the tunnel and conveys the pallets to the placing unit and then moves out of the tunnel to be reloaded. The placement unit places the pallet in the placement tool (Figure 6-3) and moves it to the desired location (Figure 6-4), where the blocks are placed (Figure 6-5). In Figure 6-6 blocks are placed close to the floor.

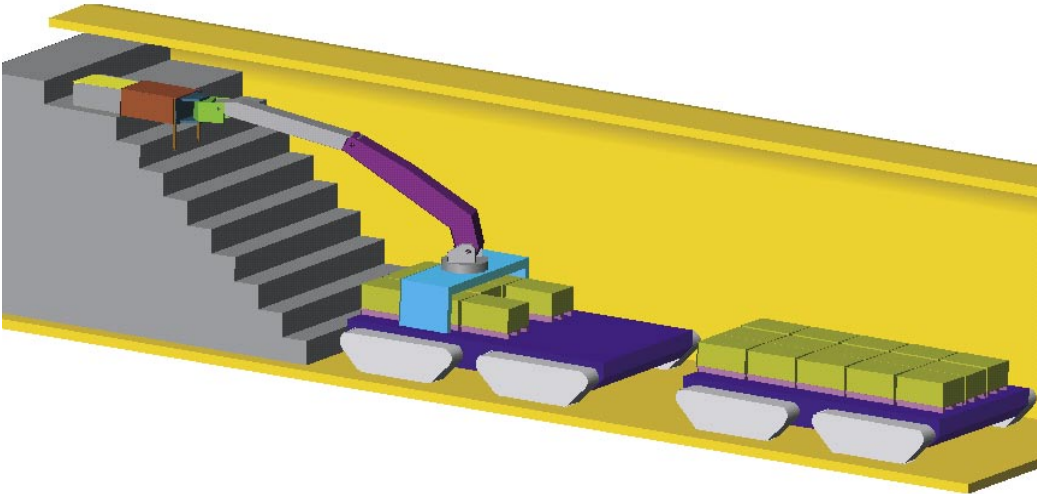


Figure 6-2. The two units for placement, one for transport and one for placement.

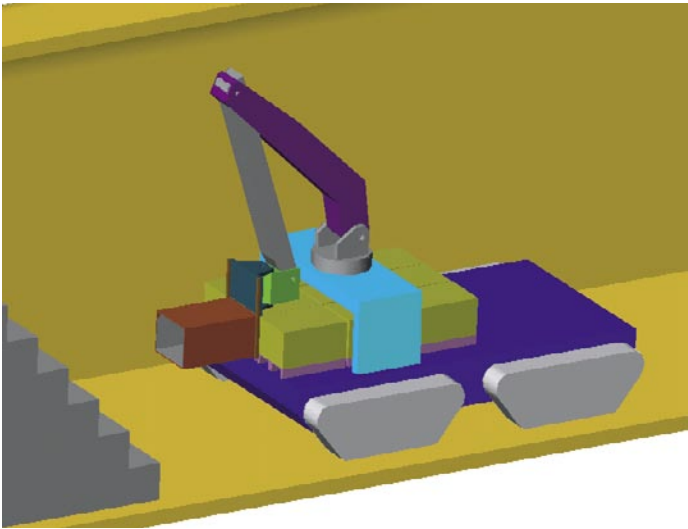


Figure 6-3. Loading the placement tool.

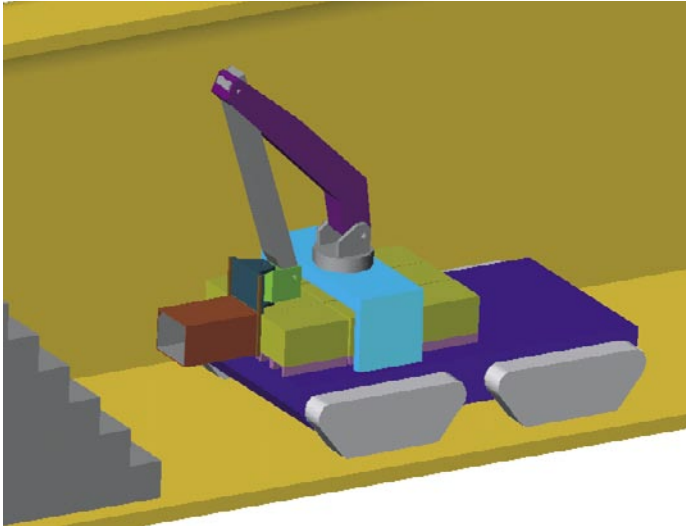


Figure 6-4. Placing the blocks at the intended location.

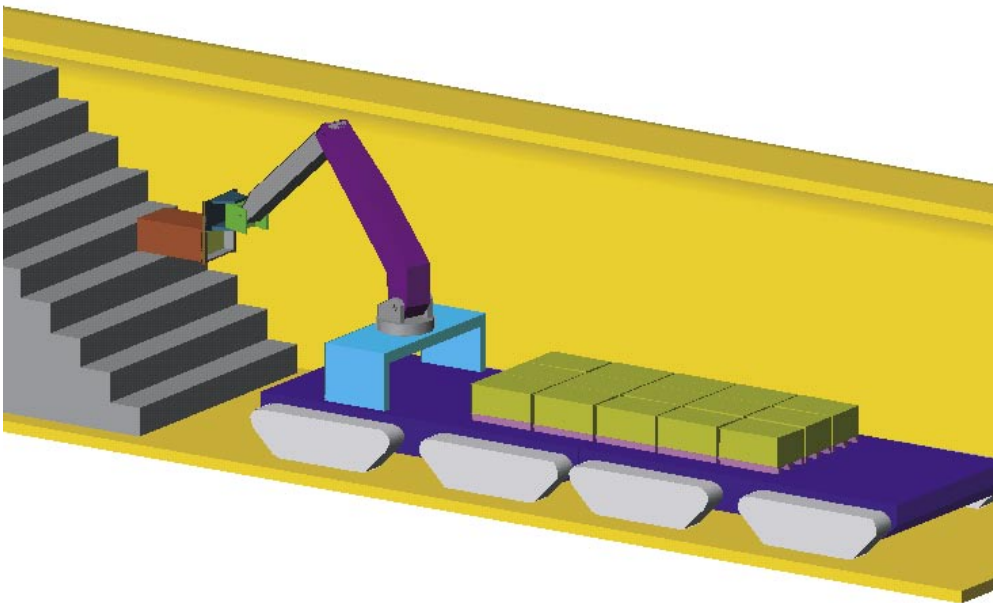


Figure 6-5. Retracting the bottom part of the placing tool.

The vehicles will be propelled by caterpillar tracks or by rubber wheels and will be powered by electricity. The cables will be led along the roof or walls. A ditch in the floor could facilitate the outflow of water. Another solution to control the water is to have perforated steel plates as a base for the block placement, these would facilitate the drainage even better. Once the tunnel is cut off by the sealing plug for the deposition tunnel, the clay will swell through the holes in the plate and the result will be a competent backfill in the entire tunnel cross-section. The plates would also provide a very flat and stable basis for the block stapling.

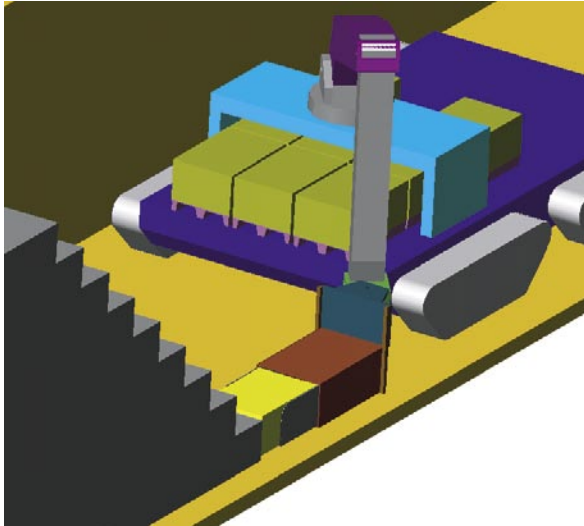


Figure 6-6. Placing blocks at the floor.

The block placement tool itself is made up by four parts: 1) an outer frame, 2) a bottom frame that can be retracted so that the blocks are left in place, this part might be a specially developed pallet that is moved out of the tunnel after the blocks have been placed, and 3) a guide that makes it possible for the frame to take two positions, one upper and one lower and 4) a flexible coupling to the “excavator arm”. The outer frame has to be able to take a lower and an upper position in order to be able to both collect blocks from the back and to dispose them at the front. The lower position is also used for deposition at the floor level.

When the placement tool is loaded it is placed in the position showed in Figure 6-3 and some kind of pusher is used for getting the blocks in the outer frame. When the blocks are placed the bottom frame is extended to the position where the blocks are placed. A holding tool keeps the blocks in place as the bottom frame is retracted.

With a desired backfilling rate of 180 m³/24h, derived from the backfilling rate 6 m tunnel per 24 h, and a pallet weight of 1 ton, a cycle time of about 3.3 min per pallet is derived if the placement equipment is assumed to work 20 hours per day. The first estimate is that this is possible to achieve. The cycle time of the transport vehicle is then 45 min if it can take 15 pallets at the time. Assuming that a reasonable average speed of the vehicle is 5 km/h and the maximum tunnel length is 300 m, the maximum transport time (back and forth) is about 7.5 min, which would mean that there are about 35 min left for loading and unloading.

Further studies are necessary to detail and improve the estimation. The filling of the top of the deposition holes and the preparation of the floor are not included, but this operation can probably be made before the backfilling starts.

The following estimation on the evolution of the block-type backfill density should apply. If other materials, like Fridland clay, are used, higher average densities will be needed.

If a standard pallet is used and 1 ton clay is disposed at a time, the dimensions of the disposed block batch will be 1200x800x520 mm. It is assumed that the cross-section of the Swedish tunnel is about 32 m² including overbreak. If the fill is 10 pallets high and 6 pallets wide, the area of the clay cross-section is 25 m³, which corresponds to a volume filling rate of approximately 78%.

If blocks with a saturated density similar to the buffer blocks, about 2050 kg/m³ corresponding to a dry density of about 1860 kg/m³, are used, the filling degree will have to be 80% to achieve an average density of 1950 kg/m³ at saturation. If this density is acceptable, no pellets will be needed.

If a higher fraction, than 80% of the tunnel cross-section needs to be filled with blocks, smaller pallets are required. If half-pallets can be used, the block-filled fraction of the tunnel will increase. However, this could slow down the backfilling rate: the larger the size of the pallet the higher the backfilling rate. These factors will have to be investigated and the pallet size optimised. If the average density of the backfill tunnel has to be raised, the remaining space can be filled with pellets. On the other hand, to have an open volume in the tunnel can be advantageous for handling water. The water can be buffered in the backfill until the position of the sealing plug for the deposition tunnel is reached. Some kind of drainage ditch in the bottom of the drift may also be considered.

The general impression is that this system would work. A number of areas for further work and questions that have to be answered have been identified:

- The detailed function of the block placing tool has to be investigated.
- The design of the pallets has to be made, and it has to be investigated whether the pallets should be integrated in the placing tool.
- The loading of the placing tool has to be designed.
- The handling of the return pallets has to be designed.
- Is it necessary for the system to handle half-pallets?
- Propelling and steering of transport unit, rubber wheels or caterpillar tracks?
- Storage capacity of transport and placement unit?
- Necessary speed for transport unit.
- The block size and shapes and the pallet size have to be optimised.
- Loading system from the truck from the surface to the transport unit.
- Are pellets necessary? If they are, a pellet handling system should be integrated in the backfilling system.
- Design of power system for the transport and placement unit.
- Block stapling tests to investigate how blocks can be piled in practice, how the mechanical properties of the blocks influence the piling and how even does the floor has to be?
- Block pressing tests.
- Levelling of the floor, can one material be used as foundation for the blocks and for the placement vehicles? What type of material is suitable?

6.1.4 Quality assurance

The control is made stepwise:

1. The material is checked and compared to specifications at delivery:
 - Geotechnical properties.
 - Chemical composition.
 - Water ratio optimised for block pressing.
 - Granule size distribution optimised for block pressing.
2. The blocks are tested:
 - Mechanical properties are compared to specifications.
 - The dry density of the blocks is measured and compared to limit values.
3. The number and weight of blocks and weight of pellets placed in the tunnel per volume is determined and the total dry density calculated and compared to specifications.

6.1.5 Application of the concept for other excavations

The material of the blocks can be chosen to fulfil the requirements of the various excavations to be backfilled. When backfilling caverns, equipment with better range has to be designed so that blocks can be placed all the way to the roof. For the shaft and ramp the expected higher water inflow needs consideration. The solution will probably be the same as for the other concepts, temporary plugs combined with some kind of drainage.

6.2 Assessment of concept D

6.2.1 Fulfilment of performance requirements

Compressibility

It seems to be possible to reach about the same density in the tunnel as in the deposition holes. If a competent material, possibly even the same as is used for the buffer, is selected, the swelling pressure would be in the same order as that of the buffer. Investigations will have to be made to determine the magnitude of the swelling pressure that is needed to keep the buffer in place.

Hydraulic conductivity

The same reasoning as for the compressibility applies.

Long-time stability

No obvious risks have been identified. If the same type of material as in the buffer is used the possibility for problems are minimized. If a material that differs substantially from the buffer is used, processes such as piping and contact erosion, may possibly occur at the interface. The risk is however low as long as the density is high and the smectite content appreciable. Most of the work directed at the long-time function of the backfill will be handled in the SR-CAN /SKB, 2003/.

Harmful effects on other/the barriers

No obvious risks can be identified. If the same type of material as in the buffer is used the possibility for problems are minimised. If there are different types of bentonite in blocks and in buffer, they might interact.

6.2.2 Technical feasibility

In general the concept seems to be feasible, but there are a number of things that need to be investigated and further developed. The main issues that can affect the feasibility negatively are related to the block-placing technique, the levelling of the floor, and as for the other concepts, the sensitivity to water inflow during backfilling.

The following issues are in focus:

1. A detailed design of the block placing system has to be worked out.
2. How the block piling works in practice needs to be investigated with special respect to:
 - Influence of the mechanical properties of the blocks.
 - Influence of the characteristics of the floor.
3. The suitability of different materials for block production has to be investigated.
4. The sensitivity to water inflow during backfilling has to be investigated.

The main disadvantage of the concept is the high cost that is a result of filling the entire tunnel cross-section with bentonite or swelling clay. One way to decrease the cost would be to investigate if mixtures of ballast and clay can be pressed to blocks.

6.2.3 Need for further studies

The continued work will be focused on investigating the feasibility of the placement technique and finding suitable material for different excavations.

To optimise the material for the blocks is a key issue. The necessary filling degree depends on the swelling ability of the blocks and on if pellets are used for filling remaining voids in the tunnel. Higher clay content makes it possible to have a lower filling degree of blocks in the tunnel. If qualified material, similar to the buffer material, is used for the blocks, bentonite pellets may not be necessary. The optimisation of material and pressing technique should be major part of the development work.

The work necessary to further investigate concept D and examine the compliance with the requirements is summarised below:

Phase 2:

- Laboratory geotechnical investigations.
- Block pressing tests.
- Water inflow tests.
- Material and technique for levelling of the floor.
- Logistics.
- Block placing tests, floor smoothness.
- Conceptual drawings of block-placing equipment.

Phase 3:

- Design drawings of block-placing equipment.
- Tests of parts of the equipment.

6.2.4 Costs

A number of different materials are considered for concept D. The preliminary cost estimation is shown in Chapter 9.

Materials

The total cost of this concept is very much dependent on the material used for the pre-compacted blocks. The materials considered in the preliminary cost estimation include activated Ca-bentonite from Milos, Friedland clay and mixtures of activated Ca-bentonite and crushed rock (30:70).

Backfill rate

The estimated backfill rate used in the preliminary cost estimations is 6 m per day (2 m/shift, three shifts per day) for the Swedish system and 2 m per day (one or two shifts a day) for the Finnish system.

Personnel

The need of personnel in this concept is at a minimum:

- Two persons for running the block manufacturing plant.
- One person for transportation of the blocks to the deposition tunnels.
- Two persons for block placement and dismantling the tunnel infrastructure.

It may be possible that more people will be needed but in the preliminary cost estimation only the minimum amount of personnel was taken into account.

Investments

The preliminary cost estimation includes a block manufacturing plant with high enough capacity to fulfil the production rate for concept D for the Swedish case. The capacity of this plant is higher than needed for the Finnish case. The investment costs for the block pressing plant designed for lower production rates has not been estimated, and therefore the block manufacturing costs per cubic meter for the Finnish case is based on the estimation made for the Swedish case and this may result in a overestimation of the Finnish costs. The investment cost includes storage for the blocks. The need for storage of raw-material is assumed to be the same for all concepts.

According to the preliminary cost estimation concept D is the most expensive concept. In addition, the risk of higher costs than expected is high due to various uncertainties concerning the technical feasibility of the concept, especially the achieved backfilling rate. The main reason for the high cost of this concept is high raw material cost and the high investment costs for the block pressing plant. If the gap between the blocks and the rock has to be filled with bentonite pellets or similar, the cost will be even higher.

6.2.5 Risk assessment

Main uncertainties

1. Can high water inflow be handled?

High water inflow will probably lead to flow through gaps and joints in the backfilling phase. Exactly how the water behaves during backfilling is hard to predict. If bentonite blocks with no pellets are used there is a large void that the water can occupy before high water pressure is built up. However, the gel that is formed in contact with the water may start to flow outwards in the tunnel and early expansion of the blocks may cause stability problems in the block placement phase. The problems will be similar if bentonite pellets are used for filling the space between blocks and rock. If this really is a problem will depend on the backfilling rate: the higher the backfilling rate, the smaller the problems with the water inflow. As for concept B, the matter can probably be handled by applying suitable technical solutions. If the water inflow cannot be decreased to low enough levels, by grouting etc, technical solutions such as drip protection and drainage can be introduced. For using drainage pipes the swelling ability of the backfill material has to be such that it can move into the drainage pipes and seal them when the drainage phase is over. The sealing process for the drainage can be facilitated if clay slurry is injected in the drainage system. For concept D the perforated steel plate suggested to be used as base for the block stapling could be used as the main drainage.

How sensitive is the concept to changes in the interpretation of the requirements? How robust is the system?

1. The concept should be fairly insensitive to changes in dimensioning salt water content of the ground water. The material and density can be adapted to a wide variety of ground water salt contents. In theory the backfill material could be bentonite replaced with the same density as of the buffer. This would meet the requirements for very high salt-water contents but it would also be very expensive.
2. Is 100 kPa swelling pressure enough for sealing channels that can result from piping during installation? For this concept the material and density can be modified to certify self-sealing after closure.

3. Other issues of concern are whether the requirements are fulfilled during the entire service time of the repository and if there are any long-term negative effects on the other barriers. These issues will mainly be handled within SR-CAN /SKB, 2003/.

No particular sensitivity for changes in the design basis has been identified.

The judgment is that the uncertainties are acceptable for continuing with the investigation of the concept. The listed uncertainties will have to be eliminated by further research and development listed in 6.2.3.

6.3 Summary and conclusions for concept D

In concept D the tunnel is filled with pre-compacted blocks that are placed in the tunnel in batches placed on pallets. The material for the concept has not yet been decided. The materials considered are bentonite, some other type of swelling clay and mixture of bentonite and ballast. If bentonite blocks are used, the remaining space between the blocks and the rock wall can probably be left to be filled by bentonite as it expands. If another material is used, the space will have to be filled with pellets to gain sufficient density for fulfilling the requirements.

The processing will depend on the type of material of the blocks. If pure clay is used, it may be possible to get the correct water ratio at delivery. If this is not the case or if a mixture will be used, the material has to be processed and mixed on site prior to block pressing. The block pressing plant is located at the site and the blocks stored under humidity control. The pallets are transported to the deposition level by truck alternatively by skip. The pallets are moved from the truck to the transport vehicle that transports it to the placement equipment at the backfilling front.

A major advantage of the concept is that since the material can be placed in the tunnel with high density the block materials can be chosen so that the design criteria concerning compressibility, hydraulic conductivity and swelling pressure are fulfilled. There are no indications that the design criteria concerning the long-term stability and harmful effects on the other barriers should not be fulfilled but this will be investigated further, mainly within SR-CAN /SKB, 2003/. The judgment is that there is high probability that the concept is technically feasible. The main problem is whether the cost is acceptable.

The swelling capacity of the backfill will be high so that channels created by piping during the backfilling can be sealed. The backfill material can be chosen so that the requirements in different excavations are fulfilled.

The technique for placement needs to be developed and the material for the blocks will have to be chosen and optimised.

The conclusion from the assessment of this concept is that the concept is promising and should be investigated further in the next phase of the project.

7 Concept E: Sandwich concept

7.1 Description of concept E

7.1.1 General

Studying the basic concepts A, B, C and D it can be observed that there are some problems and drawbacks with all of them. For example, concept A (30/70 mixture) implies difficulties in compacting the backfill and it yields hydraulic problems due to the low clay dry density. Concept C with non swelling material may yield high hydraulic conductivity. Concept D with bentonite blocks only is expensive.

The idea to combine concept C and D and still use 30% bentonite and 70% ballast material as in concept A may represent an optimum solution. Since the resulting axial conductivity is likely to be much more important than the radial, a functional idea would be to design the backfill so that bentonite blocks are placed over the deposition holes in the entire cross-section of the tunnel and crushed rock in the rest of the tunnel. Due to the composition of this structure, the concept is referred to as the “*Sandwich concept*.”

7.1.2 Layout and function of the concept

The basic idea of the sandwich concept is to use the same materials and the same overall percentage of materials as in concept A (ballast/bentonite mixture), but instead of mixing the material they are to be placed separately. The design is suggested to be as presented in Figure 7-1, with pure bentonite for about 30% of the distance between two deposition holes and crushed rock for the remaining 70%, implying bentonite in 30% of the tunnel volume. Since the crushed rock will be placed with the inclination 35 degrees, the blocks must be placed accordingly. It might also be necessary to leave a gap at the roof during installation of the crushed rock and fill it with bentonite blocks or pellets in order to avoid an open space at the roof after settlement of the crushed rock.

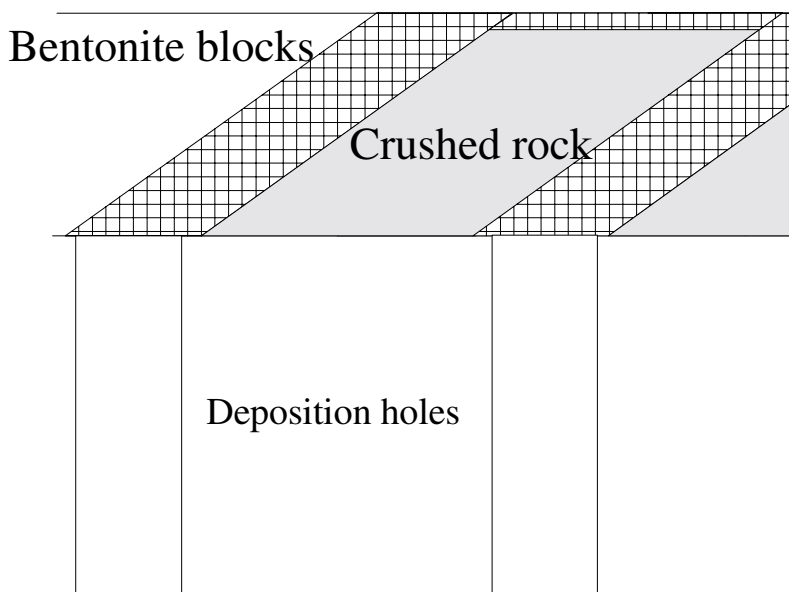


Figure 7-1. Layout of concept E.

The concept yields a number of advantages in comparison with the 30/70 mixture such as:

1. The density of the separate phases can easily be increased which means that the amount of material installed is larger.
2. The pure bentonite can be placed in block form on top of the deposition holes and thus delay water and ion transport and reduce upwards swelling of the buffer.
3. The pure bentonite can be compacted to very dense blocks yielding high swelling pressure and very low hydraulic conductivity and efficiently diminish axial flow.
4. The crushed rock may act as a water trap, which means that the water seepage from the rock fractures can fill up the voids in the crushed rock without building up large pressures for a period of time and prevent piping and erosion in the bentonite during the backfilling.

The dry density of the compacted crushed rock can, according to the tests performed at Äspö, be at least 2100 kg/m^3 . The dry density of the pure bentonite section can probably be at least as high as in the deposition hole, i.e. about 1600 kg/m^3 . This yields an average dry density of 1950 kg/m^3 , which is substantially higher than the dry density of 30/70-mixture that was reached in Äspö. At Äspö the average dry density of 30/70 backfill was estimated to be 1650 kg/m^3 . The expected average dry density in the sandwich concept is thus 18% higher. More important is that very efficient sealing for cutting off axial flow in the backfill is provided, assuming that the penetration of bentonite into the pore system of the crushed rock is small.

Such penetration caused by swelling into the pores of the crushed rock is supposed to be rather small. The only process that can cause bentonite to penetrate into the crushed rock by more than a few centimetres is colloidal transport of eroded clay by water flow. This process is, however, a bigger problem for the buffer than for the backfill and is investigated in other projects.

The drawback of concept E is the complicated logistics of placement, since two different techniques must be used. Furthermore, the hydraulic interaction of rock and the two backfill compounds is not clear: depending on the fracture system in the rock the highly permeable rock fill may give short-circuit effects. This is treated in Chapter 8.1.5.

Since this concept is a hybrid of concepts C and D, some of the items will be very briefly handled here. Instead, the main focus will be on the problems specific for this concept.

7.1.3 Materials

The bentonite blocks will be made of bentonite of MX-80 type quality, preferably the same type as used for the buffer material. The demands are high since the sealing is entirely accomplished by the bentonite section. In the preliminary cost estimation the costs were calculated assuming that the bentonite is activated Ca-bentonite from Milos, Greece.

The crushed rock will be given a grain size distribution to meet the following demands:

1. The pore system of the crushed rock section should be such that only a very limited amount of bentonite can penetrate the system by swelling or by water transport.
2. Easy to handle and compact with vibrators.
3. The hydraulic conductivity should be high enough to allow inflowing water to be collected in the crushed rock sections without building up a very high water pressure. This is contradictory to the requirement of very small voids for minimizing infiltration of smectite particles and some sort of optimization is required.

The first demand may, if found to be a problem, be solved by using more fines in the first and last layer that are in contact with the bentonite blocks. These layers would then have the function of filter layers.

The latter demand is not a requirement but a desire in order to reduce the risk of piping and erosion past the bentonite section. This process is dependent on the rate of water inflow and pressure build-up rate. It is presently investigated in another project and might turn out to be harmless in the deposition tunnels of this sandwich type.

A preliminary suggestion is to use the grain size distribution proposed (but actually not used) for the Prototype Repository. Figure 7-2 shows the grain size distribution.

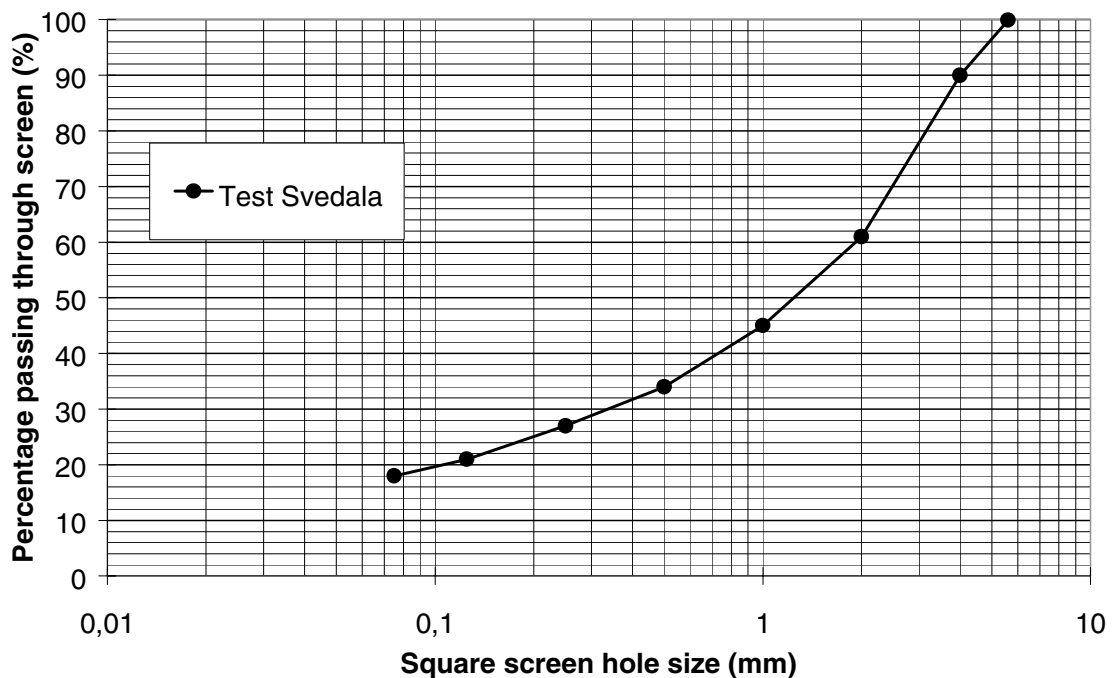


Figure 7-2. Proposed grain size distribution of the crushed rock section.

7.1.4 Material production

The material for the bentonite section will be compacted under high pressure to brick-sized blocks with techniques that resemble today's production of clay firebricks. The actual size will be adapted to the placement technique. It is probable that several sizes and shapes have to be produced, e.g. very large ones (up to 1 m³) for the central parts, smaller ones for filling the space to the roof and walls and pellets for the remaining parts. The testing and technique development will be the same as for concept D except that the layers are inclined.

The material for the crushed rock section will be produced by crushing and (possibly) milling the residual product from the rock excavation. The technique required depends on the composition of the residual products, which is determined mainly by the excavation technique but also to some extent by the rock type. Before placement and compaction in the tunnels the crushed rock must be mixed with water in order to reach optimum water ratio. Earlier investigations (mainly Proctor tests) indicate an optimum water ratio of around 6%.

7.1.5 Logistics and placement

Concept E is made up by two concepts that are treated elsewhere (concepts C and D) and description of those techniques will not be repeated here. However, it should be noted that the block technique presented for concept D is not directly applicable to this concept and that the change between placement of bentonite blocks and compaction of the crushed rock in the tunnel complicates the installation system. To which extent this slows down the backfilling rate and increases the cost is difficult to estimate and probably requires full-scale testing.

Another problem that needs to be investigated is compaction of the first crushed rock layer on the compacted bentonite block section. There is a risk that some blocks may be crushed and displaced, but this is probably not harmful for the function. Another risk is that the crushed rock penetrates between bentonite blocks during the compaction. Such a penetration must be limited to about 10 cm since it may cause flow paths.

The bentonite blocks may either be placed flat on the inclined layers or horizontally on the floor. The placement would be simplified if large blocks can be produced and if large triangle-shaped packages can be assembled and placed.

The crushed rock probably needs to be supplemented with bentonite blocks at the roof, since there will be a gap between the crushed rock and the tunnel roof. The technique for this is the same as for concept C and is discussed and described in that chapter.

7.1.6 Quality assurance

The quality control is made in similar ways as for concepts C and D. By weighing all material that is installed and measuring the coordinates of the end surface of each section, it will be possible to calculate the average density of each material section, provided that the tunnel profile is known.

7.1.7 Applicability to other parts of the repository

This concept is probably well suited for other tunnels in the repository since it allows for different lengths of the two sections and thus adaptation to the different demands that may be settled for different parts and different rock conditions. In these parts the concept may be equal to concept F (compartment concept).

7.2 Assessment of concept E

7.2.1 Fulfillment of performance requirements

The very high densities that can be reached guarantees that the mechanical properties are sufficient and that the material is stiff enough to withstand the swelling pressure of the buffer.

The net hydraulic conductivity in axial direction is very low if counted between two neighbouring deposition holes, since the low conductivity of the pure bentonite with high density efficiently diminishes all axial flow in the tunnel. However, the radial hydraulic conductivity will be rather high $> 1E-10$ m/s. It is crucial to this concept that local high hydraulic conductivity can be accepted from the viewpoint of safety analyses.

The only problem with the long-term stability that differs from concepts C and D is the contact between the two backfill components. If the crushed rock is composed according to the filter criteria this contact zone should not cause problems.

Except that the very permeable sections may provide short-circuiting of the hydraulic regime, no obvious risks can be identified. If the same type of material as in the buffer is used in the bentonite-block section the possibility for problems are minimised.

7.2.2 Technical feasibility

The combination of different materials and placement techniques will make the installation more complicated and the feasibility more difficult to assess than the other concepts. Examples of practical issues that have to be solved are how to emplace the bentonite blocks efficiently on the inclined compacted filter material surface and how to apply and compact the crushed rock or filter material on the inclined surface of the block section. The logistics will also be more complicated since different types of materials and installation equipment will be needed. This will make it harder to achieve a high backfilling rate. Penetration of crushed rock between the bentonite blocks must be prevented.

7.2.3 Need for further studies

In addition to what is needed for concepts C and D additional investigations must be made concerning uncertainties related to:

- Bentonite/crushed rock interaction.
- Placement of bentonite block on the inclined surface.
- Compaction of crushed rock on the bentonite blocks.
- Safety analysis of the effect of high radial hydraulic conductivity.
- Placement logistics.

7.2.4 Costs

The costs for concept E have been evaluated in Chapter 9. They are fairly similar to those of concept F, with the following exception:

The material used between the bentonite sections in concept E is unprocessed crushed rock, while in concept F the material will be carefully processed to gain minimum porosity and compressibility. In practice, further processing of the bulk material or use of filter layers may also be required for concept E.

Otherwise the factors that comprise the costs are similar with the concept F (see Section 8.2.4 and Chapter 9). For example, the assumed proportion of bentonite sections is similar to concept F (maximum 30 weight-percent of the total weight of the backfilling materials). Therefore it can be stated that according to the preliminary cost estimations the total costs for concept E are low (Swedish case) to moderate (Finnish case) compared to other backfilling concepts. The actual backfilling costs strongly depend on the placement rate of the bentonite sections and on the investment costs for the block pressing plant, which may be different than evaluated for concept D.

7.2.5 Risk Assessment

The separate risks for the two backfilling parts are the same as for concepts C (crushed rock section) and D (bentonite block section). Uncertainties that are specific for concept E are:

- Penetration of bentonite into the crushed rock. The risk depends on the composition and density of the crushed rock. If colloid transport is acceptable for the buffer material, it should be acceptable also for the backfill.
- Is the high radial hydraulic conductivity is acceptable in the safety analysis? This problem needs to be analysed.
- The effect of compaction of crushed rock on the bentonite blocks and the technique for placement of blocks on the inclined layers.
- The logistics of placement of the backfill with two different techniques.

7.3 Summary and conclusions for concept E

The basic idea of concept E is to backfill the tunnels with inclined bentonite sections above the deposition holes and crushed rock in-between. Bentonite blocks at the roof of the tunnel may also be necessary. 30% of the tunnel volume is filled with bentonite and the remaining 70% with crushed rock. The sections may be separated by filter materials.

The rock is crushed on site. The bentonite blocks are manufactured in a block pressing plant on site. Two different placement systems, compaction in the tunnel described in concept C, and block placement described in concept D, are used.

The design criterion concerning hydraulic conductivity is fulfilled axially but not radially. Except for this all the other criteria can be fulfilled, at least in theory. There are some practical issues that have to be solved for the technical feasibility. These problems can probably be solved but this may result in decrease of the backfilling rate and an increase of the cost.

The advantages of concept E are the following:

1. Higher densities, both clay dry density in the clay section, clay dry density distributed to all voids, even those in the crushed rock section. Higher overall average density than concept A (30/70 mixture).
2. The pure bentonite can be placed on top of the deposition hole and thus delay water and ion transport and reduce upwards swelling of the buffer.
3. Low axial hydraulic conductivity and high swelling pressure in the bentonite sections that efficiently blocks the water flow.
4. The crushed rock may act as a water trap and prevent piping and erosion in the bentonite during the backfilling.

The complicated backfilling procedure with different backfill materials and techniques in combination with the questions on if the concept complies with the performance requirement concerning hydraulic conductivity results in a recommendation not to direct any specific work at the concept in the next phase of the project. However, the results from work directed at concepts A, B and D can be utilised also for this concept. If the continued development of backfilling techniques within these concepts shows that the practical problems can be overcome and concept E is considered viable, the investigation of the concept may continue at a later stage.

8 Concept F: Compartment concept

8.1 Description

8.1.1 General

The SKB-Posiva backfilling concepts can be divided into two basic groups: homogeneous and heterogeneous concepts. Chapters 7 and 8 in this report discuss two heterogeneous concepts that named the “*sandwich concept*” and the “*compartment concept*”. In these concepts two different types of materials – clay and crushed rock aggregates – are installed separately to yield a system that performs as a whole. The hydraulic and mechanical properties of these two materials differ substantially.

The main difference between the “*Sandwich*” and “*Compartment*” – concepts is the length of the crushed rock layer, being constant in the sandwich and varying in the compartment concept /Autio et al, 2002/. In the sandwich concept, the swelling clay layers, consisting of bentonite blocks, are installed above the spent fuel canisters. In the compartment concept, the distance between two bentonite layers is flexible and will be designed at site taking the geology, hydrogeology, rock mechanics around the deposition tunnel, the pre-closure behaviour and the interactions between the backfilling material and the rock mass into account. The function of the bentonite sections is to isolate water conductive fracture zones in the rock and to seal off the deposition tunnels. Bentonite sections will also be installed at the ends of the deposition tunnels, one at the inner rock face and one inside the sealing plug for the deposition tunnel.

In both concepts, the volume close to the roof of the tunnel in the crushed rock sections is filled with bentonite blocks and/or pellets. Use of bentonite blocks around the crushed rock aggregate, so that the crushed rock section is totally insulated by using bentonite has been under discussion. Such a bentonite “candy bar” with crushed rock core could be needed in special sections such as geologically difficult sections, sections with point-like leakages, micro-fractured rock sections, etc. However, the installation of such a structure can be complicated. Further, some filter material, clay, expansive clay or fine-grained sand, at the contact surface between crushed rock and bentonite plug section and between buffer and crushed rock should be used in order to avoid physical interaction processes like intrusion of bentonite.

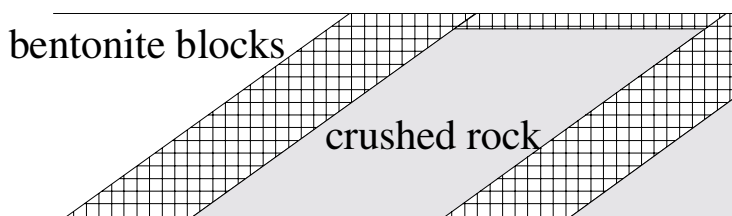


Figure 8-1. General overview of a heterogeneous backfill concept.

The excavation technique for the tunnels can probably be adapted so that the excavation damaged zone (EDZ) does not influence the long term safety. The nature of such a damaged zone, in terms of actual axial transmissivity for different excavation techniques and site conditions, is being investigated in other SKB and Posiva projects /SKB, 2001; Posiva, 2003/. If it is shown that the damaged zone could influence the long-term safety it may be considered necessary to cut off the axial flow.

One method is to excavate a notch/slot around the tunnel and fill it with bentonite blocks in order to cut off the EDZ induced pathway. Some additional clay material between the blocks and the rock is needed in the notch to fulfil the tightness requirements. Whatever material and form used, it should be impermeable and durable. The shape of the notch can be triangular (V-shape), like presented by /Autio et al, 2002/ (Figure 8-2) or rectangular like in “The Tunnel Sealing Experiment” conducted at URL /Chandler et al, 2002/. One notch could be installed per bentonite structure, but not around the crushed rock layers. In the “sandwich concept” such notches are not used.

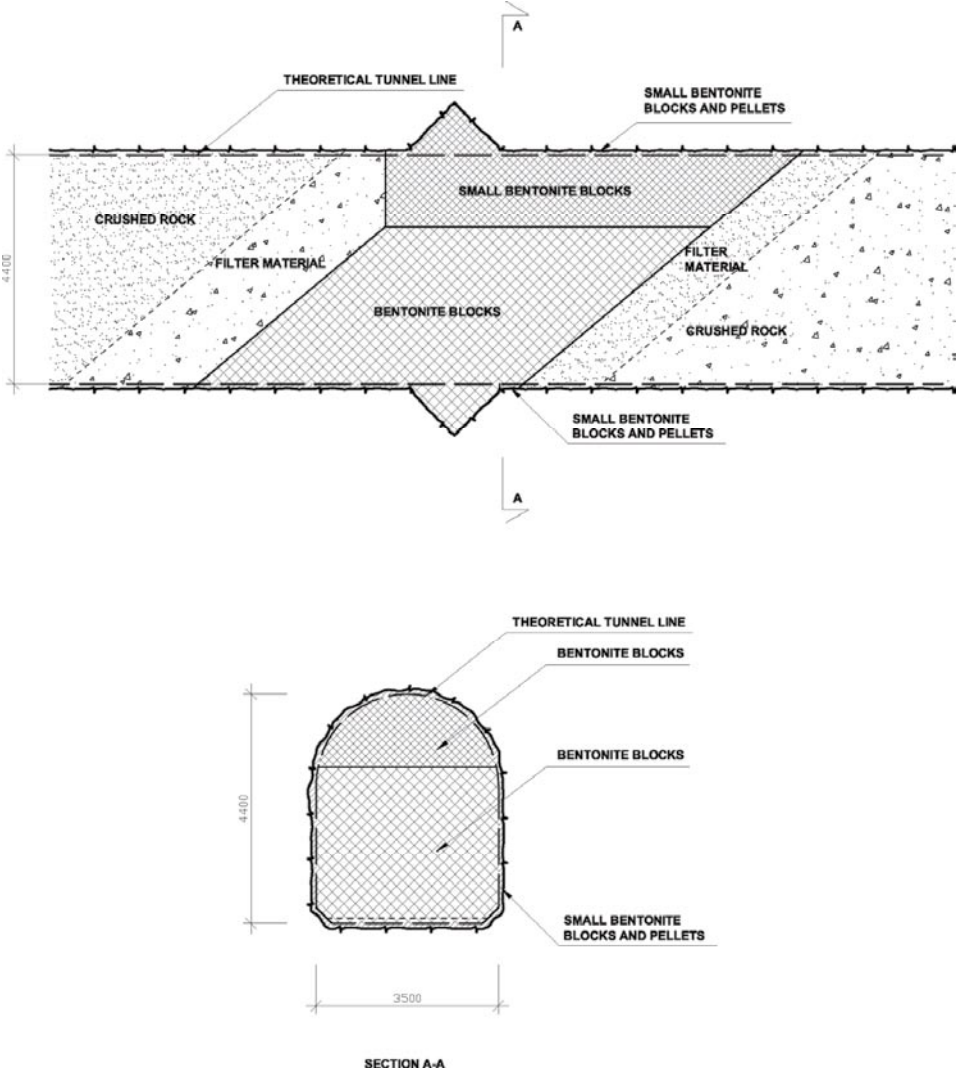


Figure 8-2. Heterogeneous compartment concept. A preliminary design of a plug of highly compacted bentonite in a tunnel backfilled with crushed rock. Two different sizes of bentonite blocks are used /Autio et al, 2002/.

As stated by /Autio et al, 2002/, additional plugs with similar structure may be constructed within the deposition tunnels, central tunnels and access routes. The final number of durable plugs in the excavations between the ground surface and a deposition hole should be designed based on the geological, hydrogeological and rock mechanical properties as well as the length and depth of the tunnel network. Earlier, when shafts were still planned to be the only accesses to the surface, 4–5 plugs between the ground surface and a deposition hole was thought to be sufficient. Since the access tunnel is now being excavated in Olkiluoto, the number of required plugs should be re-evaluated.

8.1.2 Materials in the heterogeneous backfill

The following types of backfill materials have been suggested:

- Natural clays:
 - Bentonite as bulk, pre-compacted blocks, powder, pellets.
 - Other swelling clays.
 - Non-swelling clays and other potential soil types.
- Clay mixed with crushed rock.

For the compartment concept, the main backfill volume consists of crushed rock that is intersected by zones of highly compacted bentonite blocks. Present knowledge based on the bentonite-ballast mixture backfilling implies that approximately 70% of the bulk volume is crushed rock (aggregate) and approximately 30% clay. However, in such mixture the density requirement for the bulk material and for the bentonite phase is difficult to reach, and therefore these sections of materials are separated in the Compartment concept. The crushed rock sections do not fulfil the required hydraulic conductivity limit of $1E-10$ m/s, but should reach the criterion of low compressibility. The bentonite in the plug construction between the crushed rock sections will have the form of pre-compacted blocks and pellets, providing a good hydraulic barrier. In some cases bentonite pellets might also be needed.

Crushed rock

Crushed rock aggregate will be manufactured by using the muck excavated from repository facilities. Since the main requirement of crushed rock is to provide a mechanically stable and non-compressive layer the grain size distribution should be selected based on the compaction properties. A grain size distribution of 0–5 mm with 10–15% of fines ($< 0,074$ mm) can be set as a “design value”, but should be confirmed by numerous compression and hydraulic conductivity tests.

A Fuller-shape grain size distribution curve is known to provide very high density, but it is based on spherical particles. Also, the crushability and shape of the crushed rock grains depend on the rock type and on the crushing process. In Olkiluoto for example, the schistose mica gneiss produces non-spherical (flaky/oblong) grains when crushed and processing is required to gain more cubical grains that would fit the Fuller curve better. So, the crushing process plays a very important role and should be designed and tested very carefully. By adding postglacial material like natural sand a better density may be reached. However, the various processing activities like crushing, milling or mixing necessary would raise the cost.

For the SR-CAN safety analysis /SKB, 2003/, SKB has selected crushed rock with a max grain size of 5 mm and amount of fines (< 0.075 mm) about 12%. The target amount of fines in product is very difficult to reach by normal crushing. The experiences from SKB's backfill test at Äspö shows that the muck from TBM excavation is finer graded but the shape of particles is flaky – so the crushed product does not fulfil the shape requirements for Fuller curve. Also, outside storage of materials gives problems since it absorbs water and makes handling and crushing difficult. Muck from Drill and Blast excavation is coarser, but the required shape for Fuller is easier to provide – although, the required amount (< 0.075 mm) of fines is difficult to achieve and requiring some extra proceedings.

Most likely, the crushed rock does not solely fulfil the requirements of hydraulic conductivity, but provides lot of active surfaces for adsorption.

Bentonite blocks

It is highly probable that bentonite can be pre-compacted to sufficient high density, so that the compressibility of the material is very low /Keto, 2003/. Due to the high density of the pre-compacted blocks, the material most likely fulfills the performance requirements set for the hydraulic conductivity and swelling pressure even in highly saline groundwater. According to tests made for buffer materials /Pusch, 2001/ the hydraulic conductivity of pure bentonite (MX-80) at density of 1600 kg/m³ at saturation is higher than 1E-10 m/s when salinity of the percolate was 3.5% (CaCl₂). In the same test series the bentonite sample with density of 1800 kg/m³ at saturation had hydraulic conductivity of 3E-12 m/s. So, the effect of the salinity in the groundwater is more limited than in the concept with mixture of bentonite and crushed rock as a backfill.

The bentonite plugs/sections will be constructed by using two different sizes of pre-compacted blocks (see Figure 8-2). At the center and bottom of the bentonite layer bigger blocks will be used, but at the roof (and walls if needed) smaller and tailored ones are more practical to install for following the irregular tunnel surface

The usage of compressed bentonite pellets may be a way to enhance the density of the backfill near the tunnel surface. However, it needs to be proven that bentonite pellets work as required and that a proper size of the pellets is chosen for different conditions. It has been demonstrated that the pellets with high density hydrate quite slowly and before the saturation is complete, the tunnel could function as a conductor of groundwater. Also, the final density of the pellets is found to be lower than the compacted blocks /Keto, 2003/. Also an idea to use slurry that consists of Friedland Ton clay, bentonite pellets, slag-cement and water has been presented as a possible solution in order to achieve the required density and tightness between the blocks and the rock. No tests for the material has been made, so the knowledge of long term or expansion behavior of slurry is not well known.

Pre-compacted bentonite blocks were discussed in Chapter 6.

A Filter material between the two layers

The contact of bentonite blocks and crushed rock might be sensitive for mixing of materials, since the particles/grains of bentonite are very fine in size, and the crushed rock quite porous. Assuming that the bulk material is coarse and has no self-filtering capacity, filter material should be used to hinder the expansion/intrusion of bentonite into the pore system of the aggregate layer. A suitable filter can be selected on the basis of grain size distribution data. According to /Terzaghi et al, 1996/ the “particles of the material to be protected do not pass through the filter if the D_{15} size of the filter is not larger than 4 times the d_{15} size of the coarsest base material.” In practice, a clean cohesion-less sand is a suitable filter material for silt and clay soils /Terzaghi et al, 1996/. Installation of such material to steep angle may however, be problematic.

One possible method could be to use a mixture of fine-grained sand or aggregate and other expansive clay, for ex. Friedland clay in order to create optimal filter conditions. The filter can also be in a form of pre-compacted blocks.

Another solution could be use of “The Canadian Cocktail”, of crushed rock (70%), bentonite (5%) and clay of non-swelling type (25%), /Dixon, 2000; Dixon, 2002/. Because of this non-swelling clay component the mixture has a low effective porosity resulting in a low hydraulic conductivity and high bulk density. The non-swelling clay is not very sensitive to groundwater salinity due to the relatively inert character of the non-swelling clay minerals compared to smectite group minerals. This affects the system as whole and the dense backfill has a low hydraulic conductivity and small positive swelling capacity and swelling pressure despite of saline groundwater up to 60 g/l TDS /Dixon, 2002/. However, the Filter material does not necessarily need to have any high swelling pressure.

8.1.3 Processing and mixing

As mentioned the crushed muck from the repository is a major backfill component. The crushing will take place at the ground surface.

If it is found that the required grain size distribution with high amount of fines is not gained by normal crushing, a mixing of different fractions is needed. The batching of ballast fractions will be done in a modified concrete plant mixer. The proportions of each component should be regularly controlled in the site laboratory. The production process and its rate will not be problematic – neither in crushing nor in mixing.

The mixing plant consists of silos for the aggregate fractions and the mixer that can be placed very close the crushing and/or milling stations. There can be several adjacent silos depending on the number of fractions needed. The material from the crusher can be transported by using automatically controlled conveyor belts and feeders. The mixing capacity will not be a problem, since a capacity of 1000–2000 tons per shift can easily be achieved by existing equipments.

Bentonite clay layers (Figure 8-1) will be constructed by using pre-compacted blocks.

8.1.4 Placement and compaction

There are two main techniques of applying the backfill material in the tunnels: compaction of one or two-component backfill in the tunnel, and placement of pre-compacted blocks. Both of these techniques are utilized in this concept.

Compaction in the tunnel

Crushed rock layers are installed by in-situ compaction. The material is placed in inclined layers and then compacted. The first layers could also be spread on the floor and compacted by suitable rollers. However, the feasibility of using horizontal layers depends on the amount of water leaking in the tunnel.

Compaction of inclined layers in the tunnel has been developed and tested in the Äspö HRL in Sweden since 1996 /Gunnarsson and Börgesson, 2002/. The equipment was mainly developed for compacting crushed rock/bentonite mixtures but also swelling clay (Friedton) and crushed rock compaction have been tested. The results from these tests can be utilized in the concept of compartment as well, even though some problems to fulfil all requirements were encountered.

/Pusch, 2001; Pusch, 2002/ stated that the main problem encountered during the field compaction of Friedland clay was that the compaction tool was not effective enough. In order to compact natural clays and mixtures of crushed rock and bentonite in inclined layers to high density with high efficiency, the compaction equipment has to be further developed. The main challenge is to combine the functions of the slope compactor and the roof compactor used so far, to increase the compaction efficiency by optimising the properties in terms of frequency, amplitude, force on the compacted surface etc. of the compaction equipment.

However, the compaction equipment has shown to be efficient for compacting crushed rock, which is, from the compaction point of view, a very uncomplicated material compared to a clay-based material. In the *Backfill and Plug Test* /Gunnarsson et al, 2001a/, a density corresponding to 94% of the maximum Proctor density was achieved. In the *Field Test of Tunnel Backfilling* /Gunnarsson et al, 1996/ the achieved density was near 100% Proctor. The difference between the two tests shows the importance of optimising the material composition.

Since the requirements considering hydraulic conductivity of the crushed rock sections are not as strict as for the bentonite sections, the main function of the material is to have a low enough compressibility to maintain physical stability and keep the buffer material in place. The intrusion of the expansive bentonite into the crushed rock should be managed by carefully designed filter material. Alternatively, a filter layer can be installed between these materials.

Placement of pre-compacted blocks

The bentonite plug section consists of pure bentonite mainly in a form of pre-compacted blocks. The pre-compacted blocks are placed on the compacted crushed rock layer or on the filter layer that may consist of Friedland clay and crushed rock mixture. Filter material can also be used to create a stable bed for compacted bentonite blocks.

In the description of the “Bentonite block” concept (concept D), some ideas about the placement system and equipments has been presented. However, the process of automated placement of blocks in a tunnel has not been tested either by Posiva or SKB, and no experience is available. In addition, placing the blocks on an inclined surface and in the excavated notch with high precision are challenges that were not addressed for concept D. Manual placement might decrease the effectiveness of the process and the final tightness may not be satisfactory. A hydraulic lifter and a light compactor should be designed and tested on site. The aim is to utilise the same equipment for different size of blocks.

If it is possible to use two different block sizes, larger blocks at the bottom and central part of the tunnel, and smaller blocks at the rock contact, as well as in the notch. Another option can be to use pre-compacted bentonite pellets or a bentonite-slurry. However, both these materials should be tested and evaluated in practice. Pellets can be installed by using pneumatic blowing/spraying systems as for shotcreting, but using lower pressure. Alternatively, bentonite-based slurries could be pumped with a concrete pumping system. The slurry could also be utilized as a mortar between the blocks. Also, slurry mortar tightens the possible caps/“worm holes” between the blocks and diminishes possible leakage. In the TSX-test in URL, the sprayed expansive “shot-clay” was used at the rock walls /Chandler et al, 2002/.

8.1.5 Logistics

The muck, i.e. excavated but yet unprocessed rock, is stored in the repository area. The crushing is made on the ground surface and the final product will be carried into the repository by a truck. Bentonite blocks will be manufactured either at the repository area or outside the repository area in a special factory, which is the case for pellets and for filter material as well. All the materials are stored under controlled climate and humidity conditions. The pre-compacted blocks will be transported into the tunnel by a truck using a special container that provides controlled conditions. A specially designed device for moving, lifting and placement of the blocks will be used.

The underground logistics will be complicated since many different types of materials: crushed rock, bentonite blocks, bentonite pellets and filter material, will be handled. This will slow down the backfilling process down, how much is hard to estimate at this stage, but it will to a great extent depend on the number of plugs.

8.1.6 Quality assurance

Quality assurance should start well in time before the backfilling operation. All the materials used should be automatically controlled for assuring constant and acceptable properties. The final control starts while excavating the repository, since mechanical and hydrogeological characteristics of rock mass in situ should be controlled and properly reported.

The processes and properties of the backfilling materials and the design of installation techniques need extra attention:

- Crushing and processing of rock to get a material that can be compacted to high density.
- Quality control system for different fractions of materials.
- Storage of fractions.
- Quality control of density and dimensions of the pre-compacted bentonite blocks.
- Control of compaction of aggregates and installation of pre-compacted blocks.
- Control of the filling of the remaining voids.
- Control/monitoring of the stability and movements in tunnel after backfilling.

The grain size distribution of the crushed rock will be tested regularly by dry sieving, image analysis, aerometric and laser methods. At least two of these should be used so that the results would support each other and the results could be verified to be reliable. The amount of organics in the aggregate should be controlled.

The water content, dimensions and shape of the bentonite blocks need to be controlled and surveyed after the compaction, during storage and before installation. Discarded bentonite blocks will be reprocessed.

The density of a compacted layer should be systematically measured in the field. Samples for laboratory determination (density and water ratio) will be taken at a spacing of 20–30 m in a backfilled tunnel or more frequently if necessary. Layers with too low density or softened by inflowing water will be removed and replaced with new ones.

The placement of blocks will have its own quality requirements. If there are too large gaps between adjacent blocks and/or between blocks and the roof, or the blocks have fractured during the placement, the blocks may have to be removed and replaced by new ones. Other forms of bentonite materials like pellets, powder or slurry for grouting may be considered. The allowable maximum gap between adjacent blocks and the tunnel profile needs to be determined according to further studies.

8.1.7 Application for other parts of the repository

Compartment concept can also be applied to other parts of the repository at least in tunnels (access and central tunnels), where larger and more efficient compaction devices can be used. Probably a faster and more flexible installation system and technique can be designed. Applicability of the concept for backfilling of shafts should be investigated in more detail.

8.2 Assessment

8.2.1 Fulfillment of performance requirements

Mechanical stability

In Chapter 2.1 it is stated that: “In order to maintain the density of the buffer, the backfill shall have a compressibility that is low enough to minimize the upward expansion of the buffer.” In addition, the material should have optimal grain size distribution that prevents bentonite from entering the pore system. The dimensioning ground water salt content is 3.5% (CaCl₂/NaCl, 50:50)”.

The impact of the grain size distribution and compaction technique should be evaluated aiming at the best available tightness. If aggregate the section would be “insulated” by expansive and pressurizing bentonite, and by hydraulically tight and slightly expansive filter layer between pre-compacted blocks and aggregate, it may be possible to fulfil the above stated requirements.

The expansive bentonite provides a tight plug in the tunnel. It also supports and compacts the crushed rock layer and provides a stable plug for the required ground water salt content. The long-term performance of pre-compacted bentonite blocks will be further studied in several buffer related studies.

Hydraulic conductivity and swelling pressure

There are no specific requirements concerning the hydraulic conductivity of the crushed rock and it is not supposed to have any swelling capabilities. The volume backfilled with crushed rock will have a high internal conductivity, but it may act as a sinks for contaminants and radionuclides due to the large surface area available at least in freshly crushed form /Autio et al, 2002/.

The pre-compacted blocks fulfil the stated requirements of hydraulic conductivity for the required salinity (3.5%). When the blocks are placed there might be voids remaining between the blocks and the tunnel profile at side and roof. The blocks have to be able to swell into these voids and after this have a hydraulic conductivity of 10E-10 m/s or lower and a remaining swelling pressure of at least 100 kPa. The volume of the voids will probably be in the range of 5–10%. As much as possible of this space should be filled with pellets, slurry or bentonite powder.

Long-term stability

The material should fulfil the performance requirements for a long-time period. Both the crushed rock and bentonite clay are supposed to remain relatively stable in a long-term perspective. Some minor mineralogical changes are expected due to weathering of micas to clay minerals, but these processes are slow and their effect on the geotechnical properties of these materials are believed to be small /Keto, 2003/. Studies of the long-term stability of different bentonite clays will continue within several international buffer bentonite studies.

Harmful effects on other barriers

The requirement that the designed materials should not have any harmful effect on the other barriers is believed to be fulfilled if the materials are selected carefully, taking all the other materials and barriers – like buffer bentonite – into account. In this respect, the concept performs as concept E.

8.2.2 Technical feasibility

Compaction of the crushed rock is technically feasible. The base of the crushed rock layer can be horizontal and compacted using heavy roller equipment like in road construction depending on the water inflow from the rock. The inclined layer compaction technique used in the Äspö backfilling will work well as long as backfill materials with a low amount of fines are used. Some tests including crushing and mixing provide accurate information on the most feasible way to obtain a high density. However, it should be stressed, that the hydraulic conductivity of the crushed rock layer is significantly higher than of the surrounding rock mass.

Pre-compaction of the blocks as well as pressing/manufacturing of the pellets have already been tested and found to be feasible /Pusch, 2001; Pusch, 2002/. Handling of blocks during placement in the tunnel can be made by utilizing slightly modified versions of existing lifting and handling equipment. If available equipment for blowing of pellets and/or pumping of slurry cannot be used, further detailed design is required.

The combination of different placement techniques: placement of blocks, compaction by vibration in the tunnel, and pellet blowing or slurry pumping may make the backfilling complicated and time consuming. The application and compaction of the first layer of crushed rock on the surface of the bentonite blocks in the plug section and the placement of bentonite blocks in the notches may be particularly problematic.

8.2.3 Need for further studies

The following properties of backfilling materials and the design of installation system should be tested:

1. Crushing of rock for reaching suitable densities:
 - 2–4 different grain size distributions from each source rock type, more fines may be required, more tests needed.
 - Crushability of different source rock types, development of optimal crushing, screening and mixing processes.
 - Sampling and quality control of ballast material.
2. Bentonite block compaction and placement – same as for the sandwich concept.
3. Density, mechanical behaviour and hydraulic conductivity of the whole system should be defined:
 - Stability while emplacing the blocks.
 - Expansion of bentonite under different water leakage conditions.
 - Filling of the empty space around blocks due the irregular and rough tunnel surface caused by natural shistocity and jointing as well as by excavation –pellets in varying size or slurry may be a solution.
 - Aggregate – block contact (Filter material).
4. Installation and in-situ compaction equipment.
5. Shape of the notch excavated around the tunnel.

8.2.4 Costs

The cost of heterogeneous backfilling can be divided into raw material, production of components, labour, transportation and investments for equipment. In addition, there are some minor fixed costs like energy, water and insurance etc. Several open questions of the presented backfilling concept still exist the solutions to the questions may affect the cost. The cost for development is difficult to estimate but should be considered.

Backfilling, including crushing, mixing of aggregate fractions, production of pre-compacted bentonite blocks, transportation inside the repository area, and backfilling will be made in campaigns. Three shifts per day are required in the Swedish system, while one to two shifts per day is needed in the Finnish system to reach sufficient backfilling rates.

Raw materials

The material costs are highly dependent of the ballast/bentonite ratio, which is determined by the number of the pre-compacted bentonite plugs required in each tunnel and by their thickness. In the preliminary cost estimation it was assumed that the proportion of sections filled with bentonite blocks is maximum 30 weight-percent of the total weight of the backfill. This is equivalent to 27.4 volume-percent of the total tunnel volume. However, in reality the cost is difficult to evaluate without knowledge of the hydrogeological and geological properties of the host rock. It is possible that the proportion of bentonite according to this concept will be lower than 30 weight-percent depending on the hydrogeological conditions. This would reduce the raw material costs significantly compared to concepts A and E and this was an expected benefit of this concept.

As an example:

According to the repository layout for Olkiluoto the canister spacing is 10 or 9 m depending on fuel type. The length of the deposition tunnel is typically around 300 m, and the amount of unsuitable rock approximately 17% (Äikäs et al, 2000). The number of plugs will depend on the local geology and hydrogeology.

The cost of the major volume of backfill material is quite low if the muck from the repository can be utilized. Normal transportation, loading and crushing is quite simple. If a very high proportion of fines is required, this affects the Euro/ton cost, since extra milling or grinding and drying is needed. Also, there is a need of tight silos for storage of crushed rock material to avoid wetting, dusting and contamination of the material.

If post-glacial sand or some fine crushed materials will be used in addition to the crushed rock, they will be purchased from a subcontractor, who will be responsible for excavation, pre-processing, transportation, quality checking and storage of the material on the repository site. Only the final quality control should be made at repository site well before use.

Bentonite, including re-processing and transportation to the site, will be purchased from an exporter or directly from a producer. Pre-compaction of the blocks are made at the repository site. It should be decided whether the slurry and the pellets will be manufactured at site or purchased from a subcontractor.

Personnel

In the preliminary cost estimation it was assumed that two persons per shift are needed for block manufacturing, one person for material handling and one more for process and quality control, one shift per day in both cases.

The mixing and quality control of crushed rock materials should be automatic and handled by one person/shift. Also, one person is needed for transportation and loading of the raw materials to the mixing plant if the material is not already crushed and stored in silos near the mixer and transported by using conveyor belts. If the volume of the silos is big enough, the loading can be done only in one shift per day.

One person per shift is required for transportation of pre-compacted blocks and the back-filling mixture to the deposition tunnel, or alternatively to a temporary storage located on the repository level. If temporary underground storages are used, one person/shift is needed for transportation of backfilling materials from the temporary storage to the deposition tunnel.

One to two persons per shift are needed for dismantling the infrastructure from the tunnel, operating the equipments needed for spreading the material to form inclined layers, compaction of the layers, preparation of the upper backfill surface and placing the blocks.

Two foremen per shift are required; one for above ground activities and one for underground works. These two should be qualified for the quality control of different procedures and materials including the final backfill.

In summary, the need for personnel per shift in concept F is:

- Crushing: 1 person.
- Mixing and surface transportation of the aggregate: 1 person (+ crushing person).
- Pre-compaction of bentonite blocks: 1–2 persons.
- Transport of materials to the repository level: 1 person.
- Transport of materials into the disposal tunnel: 1 person.
- Tunnel preparation, operation of backfilling equipments: 1–2 persons.
- Shift foremen for charging the activities and for quality control: 1 person.

In the preliminary cost estimation it was assumed that an average of 2 persons per shift is required for underground operations such as dismantling the tunnel infrastructure, compaction of the bulk backfill and installation of the blocks). The personnel cost is included in the estimations for transportation costs (400 Euro/shift) and the mixing costs (20 Euro/m³).

Backfill rate

The required backfill rates are 10 m/week for the Finnish system and 6 m/day for the Swedish system. The estimated backfill rates used in the preliminary costs estimations (Chapter 9) are the following:

- Finnish system: 2 m/shift for the inclined layers and 1.75 m/shift for the backfilling blocks, including filling of the gap manually.
- Swedish system: 1.5 m/shift for the inclined layers and 1.75 m/shift for the backfilling blocks, including filling of the gap manually.

It should be noted that the backfilling rate is difficult to estimate since the backfilling will comprise different material and installation techniques that have not been tested yet.

There is a risk that construction of the bentonite section will be slower than assumed, especially in the case of manual block placement. Also, the excavation of a notch for bulkheads should be taken into a consideration while scheduling the entire construction process.

The capacity of the equipment for crushing and mixing of rock components available on the market is higher than required even if extra grinding or milling is required. For the Finish case the mixing could be made in one shift and the material intermediately stored in box-feeders or similar. For the Swedish case the mixing may be done in three shifts for avoiding the need of large storage facilities.

The following aspects should be considered when estimating the costs for phase 2:

- Characterization of plug sites and excavation of notches.
- Extra milling of crushed rock.
- Examining of the required thickness of the bentonite sections considering that emplacement of bentonite blocks is much slower than the application of crushed rock and filters.
- Application of a bentonite block layer around the entire perimeter of the tunnel for estimating its impact on the rate of backfilling.

Investments

The equipments and facilities used for backfilling will induce high investment costs. Some operations can preferably be supplied by a subcontractor, like crushing and transportations, at least above ground. As stated before, most of the equipments need further design and testing, which should be taken into account in the final economical evaluation. Naturally, it is economically favourable to use equipments that can be applied for several purposes like, e.g. for compaction in the tunnel, block installation, and pellet blowing. The main issues are:

- Crushing and grinding – subcontractor.
- Storage of crushed rock – covered pile for coarse material and silos for finer fractions.
- Mixing plant – Since no clay will be used in the mixture a quite simple mixer is sufficient. Extra costs for automatic sampling and controlling systems may arise.

Pre-compaction facility with mixer, press and moulds – expensive, but definitely needed.

- Storage facilities for the bentonite blocks and mixed rock components (silos).
- Transport equipments for bentonite, bentonite blocks and mixtures.
- Underground transport vehicles.
- Compaction equipment.
- Equipment for placing the blocks.
- Equipment for bentonite pellet blowing and slurry grouting.

The investment costs mentioned above have been taken into account in the preliminary cost estimation excluding the storage facilities for raw materials, and equipment for pellet blowing and grouting.

According to preliminary cost estimations the cost for concept F is moderate compared to other backfilling concepts. In practice, the actual cost strongly depends on the spacing and thickness of the bentonite sections, the actual investment cost for the block manufacturing plant (which may be different than for concept D), and on the installation rate of the sections filled with the bentonite blocks.

The cost estimation is based on drill and blast excavation of the notches, if a more sophisticated technique, like seam boring or sawing, is considered necessary; the cost for the concept will rise significantly.

8.2.5 Risk assessment

Due to the heterogeneity of the concept, it does not thoroughly fulfil the performance requirement considering low hydraulic conductivity in the entire tunnel cross-section. Therefore a discussion and re-interpretation of the requirements set for the backfill will be necessary. However, this concept provides a system where the mechanically stable aggregate body is insulated and plugged by the expansive pre-compacted bentonite blocks that have suitable properties required for a hydraulic barrier. In addition the crushed rock aggregate layer provides a huge active surface for adsorption.

The most obvious risks of this concept are linked to the hydraulic conductivity of the crushed rock section and to possibility of contact erosion between fine and coarse materials, e.g. between the buffer bentonite and the aggregate. The high hydraulic conductivity of the crushed rock sections may be critical depending on the rock structure and hydrology. To judge whether this is acceptable requires further assessment of the long-term safety of the system. The problem with fine particle migration can be solved by modifying the grain size distribution of the crushed rock and by installing a filter between fine and coarse materials. This would, however, increase the cost.

There is also a risk that the relatively complicated backfilling procedure slows down the backfilling rate and increases the cost.

8.3 Summary and conclusions for concept F

The basic idea of this concept is to divide the deposition tunnel into two types of sections. The main volume, at least 70 weight-percent, of the tunnel is backfilled with crushed rock with a thin layer of pre-compacted bentonite blocks at the roof. The crushed rock sections are separated by plugs consisting of highly compacted bentonite blocks. The plugs are extended into the rock to cut off the EDZ, the excavation damaged zone. The location and distance between the plugs is designed based on the local geology and hydrogeology.

The rock is crushed and processed to an optimized grain size distribution. This result in good compaction properties, low compressibility, and prevents contact erosion between the crushed rock and the clay. The crushed rock is compacted in inclined layers in the tunnel. Filter layers of suitable material are installed between the plug and the crushed rock sections to avoid mixing of these materials. The plugs are constructed of blocks of different sizes. The blocks, both for the plug and for the roof section, is manufactured in a block pressing plant in the repository area. Quality control will be integrated into all steps of the backfilling process.

The concept fulfils the design criterion concerning compressibility, while the hydraulic conductivity and swelling pressure criteria will only be fulfilled for the bentonite plug sections. The plug sections keep the axial hydraulic conductivity low while the radial conductivity of the crushed rock sections will be high.

There is no indication that the criteria considering long-term stability and no harmful effects on the barriers would not be fulfilled. The main questions concerning the technical feasibility of the system are whether the bentonite plugs can be placed with sufficient efficiency, and how the practical issues concerning the interfaces between the two types of sections can be solved. The costs for concept F are moderate compared to the other concepts but the complicated installation procedure may increase it significantly. The cost estimation is based on the use of conventional drill and blast technique for excavating the notches. If a more careful excavation technique is considered necessary the cost will be significantly higher and will to an even greater extent depend on the amount of plugs.

The positioning of the plugs would have to be based on a thorough understanding of the local hydrogeology and the process for choosing the locations would be complicated. The notches filled with highly compacted bentonite with the purpose to cut off a possibly excavation damaged zone should not be associated only with this particular backfilling concept but with the existence of an excavation damaged zone with an axial transmissivity that influences the long time function of the repository. Since it is believed that no such zone is created if the excavation is made in a correct way this type of notches will not be studied further in the project. However, if further studies on the EDZ-issue /e.g. Posiva, 2003/ will prove this assumption wrong, design of an engineering solution will be re-started.

The complicated backfilling procedure with different materials and techniques, in combination with the question on if the concept complies with the performance requirements concerning hydraulic conductivity result in a recommendation not to direct any specific work at the concept in the next phase of the project. However, the results from work directed at concepts A, B and D can be utilised also for this concept. If the continued development of material and backfilling techniques show that the practical problems can be overcome and concept F is considered viable the investigation of the concept may continue.

9 Preliminary cost estimations for different concepts

Preliminary cost estimations were made for each concept both for the Finnish and Swedish cases. In general, the costs for backfilling can be divided into three main categories:

- Costs for research and development work.
- Costs for raw materials.
- Investment, work on site, upkeep and other costs linked to processing, manufacturing and installation of the backfill material.

The development and research costs were excluded from the estimation, since it is difficult to evaluate these costs reliably at this stage of the project. However, it was stated that the concepts requiring development of new techniques will probably create higher development and research costs compared to concepts for which proven technique can be used. Furthermore, new types of materials require some extra research work in order to evaluate their chemical and physical effect on the other repository barriers in a long-term perspective.

Raw material prices and other costs linked to processing, manufacturing and installation of the backfill were estimated per cubic meter in order to evaluate the average backfilling cost per meter tunnel length. The raw material prices per cubic meter (Euro/m³) depend on the ton price (Euro/t) for different materials, density of the materials, the proportions of different materials within the backfill, e.g. proportions of bentonite and ballast, and on the initial water content of the materials. Costs other than that of raw materials depend on the backfilling rate, efficiency of backfilling, investment costs for different equipment and facilities, need for personnel, and on the energy, upkeep and maintenance. Due to the difference in required efficiency of the backfilling procedures between the Finnish and Swedish systems, the costs are higher for the Finnish case than for the Swedish case. The required backfilling rate for the Finnish tunnels, with theoretical cross-section area of 14 m², is only 10 m/week. The required backfilling rate for the Swedish tunnels is 6 m/day and the theoretical tunnel cross-section 29 m².

The basic assumptions used in the cost estimations for different concepts are summarized in Table 9-1.

The assumed amount of personnel taken into account in the calculations are: 2 persons per shift for underground operations (compaction, installation, dismantling the tunnel infrastructure) in all of the concepts, and 2 persons per shift for running the pre-compaction plant (C, D, E and F). The personnel costs linked to mixing the bulk material (in A, B, C and E) and transportation (all concepts) are included in separate cost estimations for the task. In addition, 16% for maintenance and overhead costs has been included in these estimations.

Table 9-1. Basic assumptions used for preliminary cost estimations for different concepts.

Basic assumptions	Concept A	Concept B	Concept C	Concept D	Concept E	Concept F
Materials	Mixture of ballast (crushed rock) and bentonite (MX-80 Na-bentonite or Milos activated Ca-bentonite).	Friedton (Friedland) clay (mixed-layer clay with swelling ability).	Fine-rich till (non-swelling soil type) and bentonite (Milos activated Ca-bentonite).	Bentonite (Milos), Friedton or mixture of ballast and bentonite.	Ballast (crushed rock) and bentonite (Milos).	Ballast (crushed rock + layer of filter material consisting of bentonite) and bentonite (Milos).
Proportion of materials (weight-percent)	30% bentonite, 70% ballast.	100% clay.	Ratio of bulk material and blocks 95:5. Bulk material: 5% bentonite, 95% fine-rich till. Blocks: 100% bentonite.	Clay blocks: 100% clay (Bentonite, Friedton). Mixture blocks: 30% bentonite and 70% ballast.	Ratio of bulk material and blocks 70:30.	Ratio of bulk material and blocks 70:30. Bulk material: 95% crushed rock, 5% bentonite as a layer. Blocks: 100% bentonite.
Final dry density in the tunnel (t/m ³)	1.7 t/m ³	1.6 t/m ³	Bulk material: 1.9 t/m ³ Blocks: 1.7 t/m ³	1.7 t/m ³	Bulk material: 1.7 t/m ³ Blocks: 1.7 t/m ³	Bulk material and filter: 1.5 t/m ³ Blocks: 1.7 t/m ³
Assumed backfilling rates	2 m/shift (FIN), 1.5 m/shift (SWE).	2 m/shift (FIN), 1.5 m/shift (SWE).	Bulk material: 3.2 m/shift (FIN), 2.25 m/shift (SWE). Blocks: 1.75 m/shift (FIN and SWE).	2 m/shift (FIN and SWE).	Bulk material: 2 m/shift (FIN), 1.5 m/shift (SWE). Blocks: 2 m/shift (FIN and SWE).	Bulk material: 2 m/shift (FIN), 1.5 m/shift (SWE). Blocks: 1.75 m/shift (FIN and SWE).
Techniques	Compaction in the tunnel.	Compaction in the tunnel.	Compaction in the tunnel and pre-compaction.	Pre-compaction.	Compaction in the tunnel and pre-compaction.	Compaction in the tunnel and pre-compaction.
Investments	Mixing plant, compaction device, transportation equipments.	Mixing plant, compaction device, transportation equipments.	Mixing plant, block pressing plant, compaction device, transportation equipments.	Block pressing plant, installation device, transportation equipments.	Mixing plant, block pressing plant, compaction and installation device, transportation equipments.	Mixing plant, block pressing plant, compaction and installation device, transportation equipments.

The average backfilling costs for the different concepts per meter tunnel length for the Finnish case are presented in Figure 9-1 and the costs for the Swedish case in Figure 9-2. These estimations should be considered only as approximate and relative estimations, since the basis of the calculations includes various sources of uncertainties. The main ones are: future raw material prices, achieved backfilling rates, efficiency of the processes, amount of working days per year, future personnel costs, investment costs, service time for different equipments and reliability of backfilling equipments/need for extra maintenance. Most of these uncertainties concern material investment and operation costs linked to processing, manufacturing and installation of the backfill (red and yellow columns). For example, if the backfilling rate in concept D (Swedish case) would be only 3 m/day, instead of the required 6 m/day, the costs other than for the raw material would be doubled.

As already mentioned, the other than raw material costs are relatively higher for the Finnish system than for the Swedish system, especially in concepts where pre-compaction of backfilling blocks is required (concepts C, D, E and F). This is due to remarkably lower backfilling rate compared to the Swedish system. In addition, the investment costs for the block pressing plant were only estimated for concept D for the Swedish case, and it is possible that the investment costs can be somewhat lower for a smaller plant, in which case the costs for the pre-compaction might also be somewhat lower.

According to these preliminary estimations, the cheapest backfilling concept is, due to low material costs, concept C and the most expensive is concept D, in the case the tunnel is filled with blocks made of 100% bentonite clay. Some of the uncertainties linked to these prices will be further investigated in the next phases of the project, e.g. the backfilling rates, investment costs etc. However, the backfilling costs are also influenced by factors that depend on international price development, for work and materials, and must therefore be regarded as preliminary cost estimates.

Backfilling costs (euros per tunnel meter) FIN

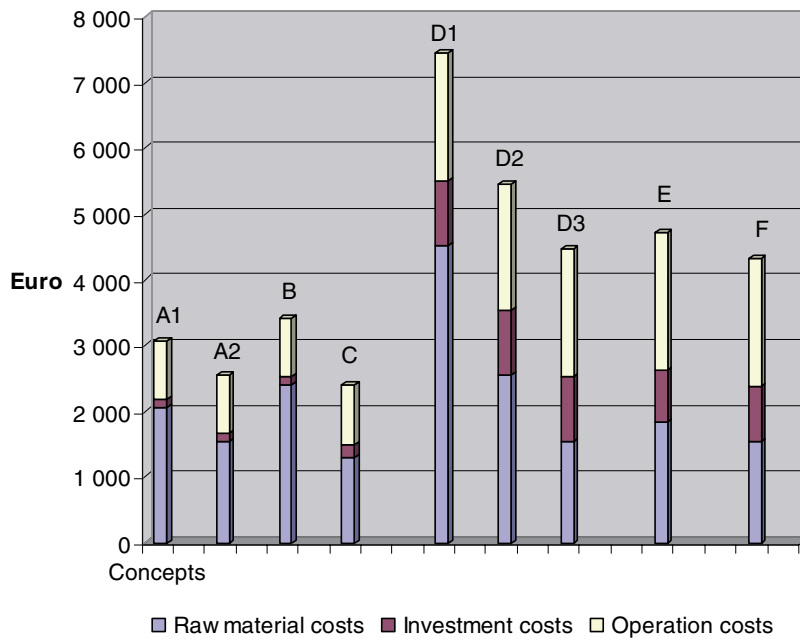


Figure 9-1. Estimated costs (euros) per one tunnel meter (in the Finnish system). Symbols **A1** = concept A with MX-80 bentonite, **A2** = concept A with activated Ca-bentonite (Milos), **B** = concept B, **C** = concept C, **D1** = concept D with blocks made of activated Ca-bentonite (Milos), **D2** = concept D with blocks made of Friedland clay, **D3** = concept D with blocks made of mixture of activated Ca-bentonite and crushed rock (30:70), **E** = concept F and **F** = concept E.

Backfilling costs (euros per tunnel meter) SWE

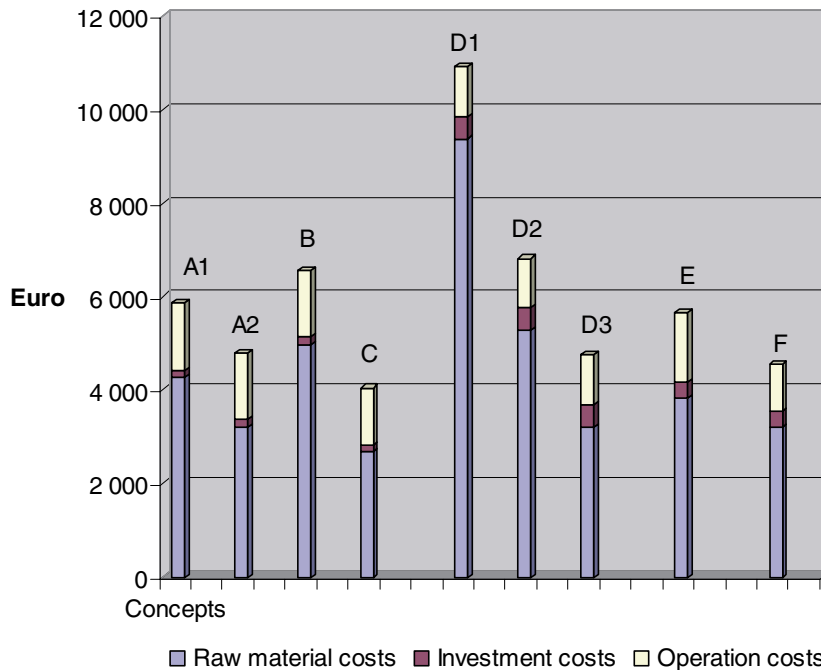


Figure 9-2. Estimated costs (euros) per one tunnel meter (in the Swedish system). Symbols: **A1** = concept A with MX-80 bentonite, **A2** = concept A with activated Ca-bentonite (Milos), **B** = concept B, **C** = concept C, **D1** = concept D with blocks made of activated Ca-bentonite (Milos), **D2** = concept D with blocks made of Friedland-clay, **D3** = concept D with blocks made of mixture of activated Ca-bentonite and crushed rock (30:70), **E** = concept F and **F** = concept E.

10 Recommendations for further work

The recommendation is that the following concepts will be further investigated in phase 2 of the project:

- Concept A, compaction of bentonite/ballast mixture in the tunnel.
- Concept B, compaction of expandable clay in the tunnel.
- Concept D, placement of pre-compacted blocks.

For phase 2 no work will be directed at:

- Concept C, compaction of non-swelling clay in the tunnel with bentonite blocks at the roof.
- Concept E, sandwich concept.
- Concept F, compartment concept.

If new knowledge that changes the conclusions in this report is gained the work on concepts C, E and F may be re-considered.

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